Reflections on developments in the area of supersonic combustion

Prof. H S Mukunda , CGPL - Dept of Aerospace Engg - IISc

Issues from the past

- Reduced mixing at high Mach numbers would have severe impact on scramjet combustor design in the late eighties
- Hints of "introducing an isolator between the intake and the combustor would be necessary"
- Design for high degree of combustion, but not complete

Background

- 1986 is an important demarcation year
- Earlier conceptual, experimental and developmental work seems to have been conducted in an uninhibited manner.
- Most later work has had the effect of the Cal Tech findings on reduced mixing at high Mach numbers – searching for better mixing techniques became an obsession

Why discuss these now?

- There have been five flight tests to demonstrate supersonic combustion or better, to demonstrate autonomous supersonic flight.
- The Russia-France and Russia-NASA flight tests on a Russian vehicle have shown supersonic combustion in one flight and there were problems with others.
- The Australian test was more an add-on of supersonic combustion demonstration with no clear vehicle aspects in mind.

Why discuss these now? - 2

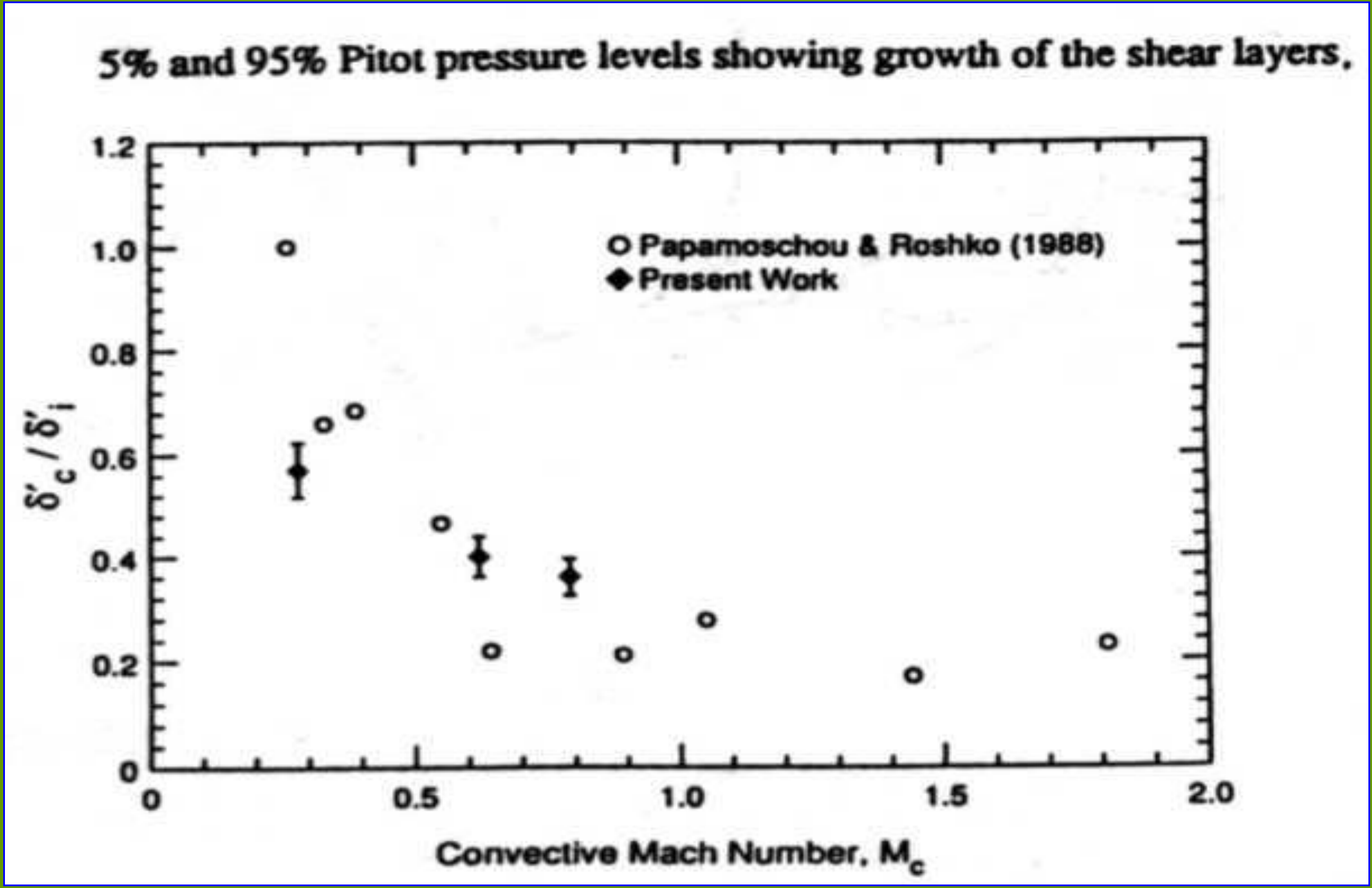
- The lack-luster performance of the multi-country effort with hype on the difficulties associated with the mixing/combustion issues caused by fluid dynamicists have led progressive S & T investors of being shy in supporting aggressive R & D efforts.

- Also, "young" scientists get carried away by the hype and may make additional contributions to impediments in investments.

  - This is why it is necessary to review and draw upon the critical past that is "good".

Reduced mixing at High M

Ikawa H and Kubota T (1975), Papamoschou and Roshko (1986), Clemens and Mungal et al (1990)



Analysis of the mixing behavior

$(\delta/x) = C_1 (u_2 - u_1)(1+\sqrt{s}) / (u_2+u_1\sqrt{s})$ x $[0.2 + 0.8 \exp\{-2(u_2 - u_1)^2/(a_1 + a_2)^2\}]$

where δ/x is the shear layer growth rate and s = density ratio, ρ_2/ρ_1,

C_1 = constant ~ .17

- **Note that when u_1 is held fixed, but u_2 is varied, the growth rate increases due to "incompressible" terms and decreases due to compressibility effect. This leads to a local maximum in the growth rate.**
- **Typically, u_1 = fuel speed ~ 1500 to 2000 *m/s* (H_2, M = 1, T ~ 900 K)**
- **Air speed, u_2 ~ 1650 to 2000 *m/s* (M ~ 2 to 2.5, T ~ 1000 to 1400 K)**

$(u_2 - u_1)$ ~ 200 to 300 *m/s*, Convective Mach numbers will be < 0.4

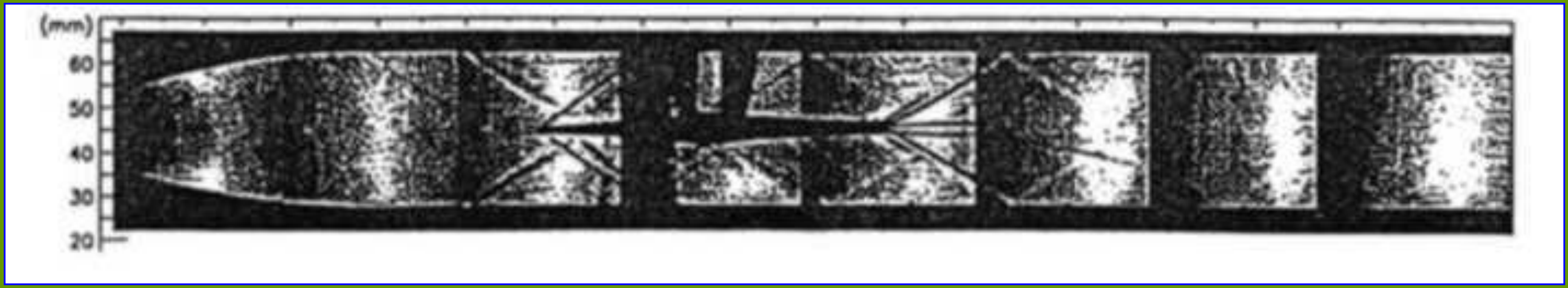
- **The dynamics for liquid fuel injection will be affected in addition by spray dynamics as well as coupled gas dynamics**
- **Is there any problem due to compressibility at all?**

Let us therefore look at

Experiments on mixing

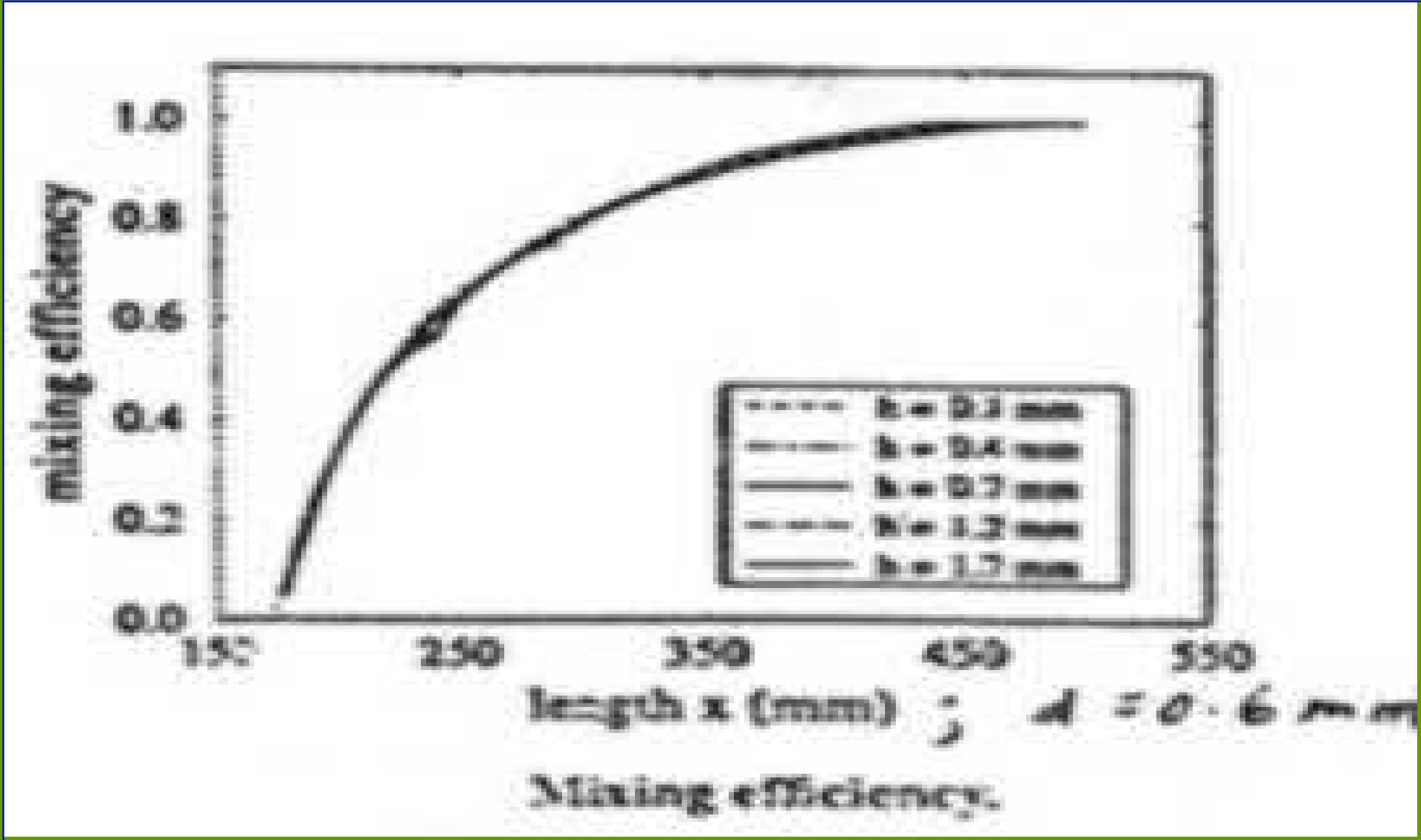
a. Gerlinger and Bruggeman, 2000
b. Uneshi, Rogers and Nortam, 1989
c. Gruenig, Avarshikov and Mayinger, 2000
d. Wilhelmi Baelt and Bier, 1973
e. Guoskov, Kopchenov, Vinogradov, and Waltrup, 2001
f. Henry, 1969

Gerlinger and Bruggeman, JPP, pp. 22 - 28 (2000)



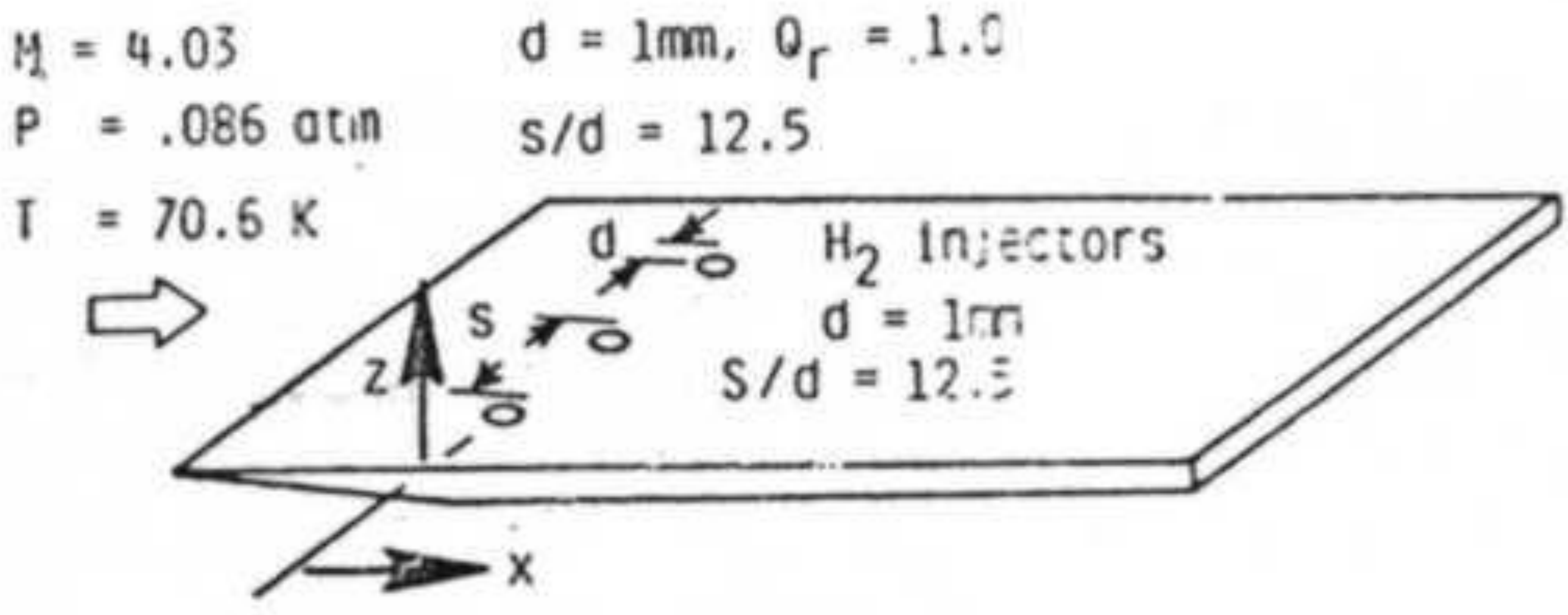
- Parallel injection, High convective Mach number; only mixing question is being addressed.

Gerlinger and Bruggeman, JPP, pp. 22 - 28 (2000)



Mixing is fast in the early stages. Mixing for 95 % efficiency is 430 mm (x/d = 700 with parallel injection)

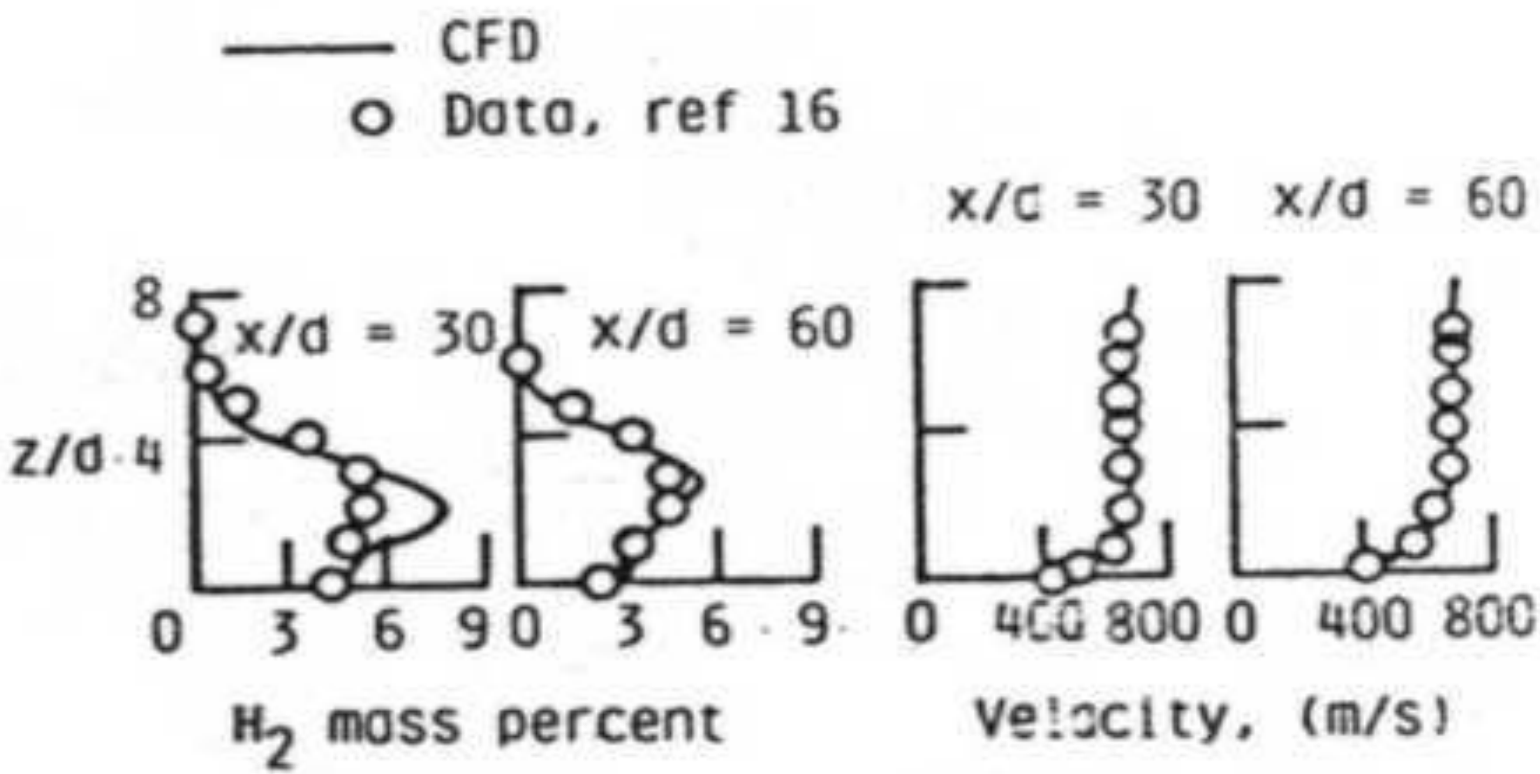
Uneshi, Rogers and Northam, JPP, pp. 158 - 164 (1989)



a) Schematic of experiments

Perpendicular injection; only mixing related issues are of interest

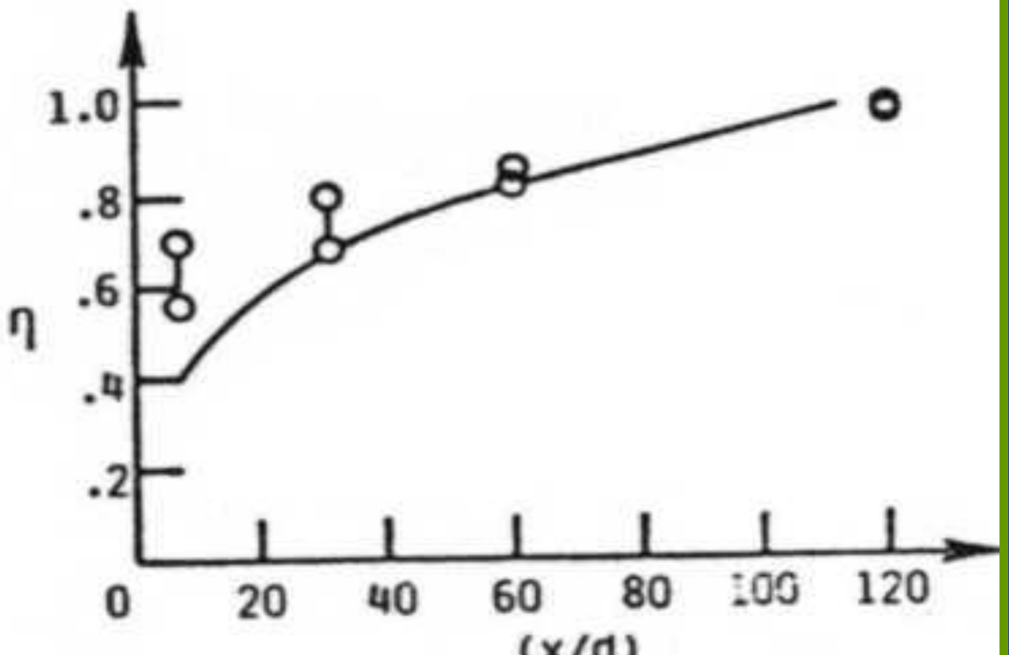
Uneshi, Rogers and Northam, JPP, pp. 158 - 164 (1989)



b) Comparisons at jet centerline

CFD – prediction of composition (mixing) seems very good.

Uneshi, Rogers, Northam, JPP, pp. 158 - 164 (1989)

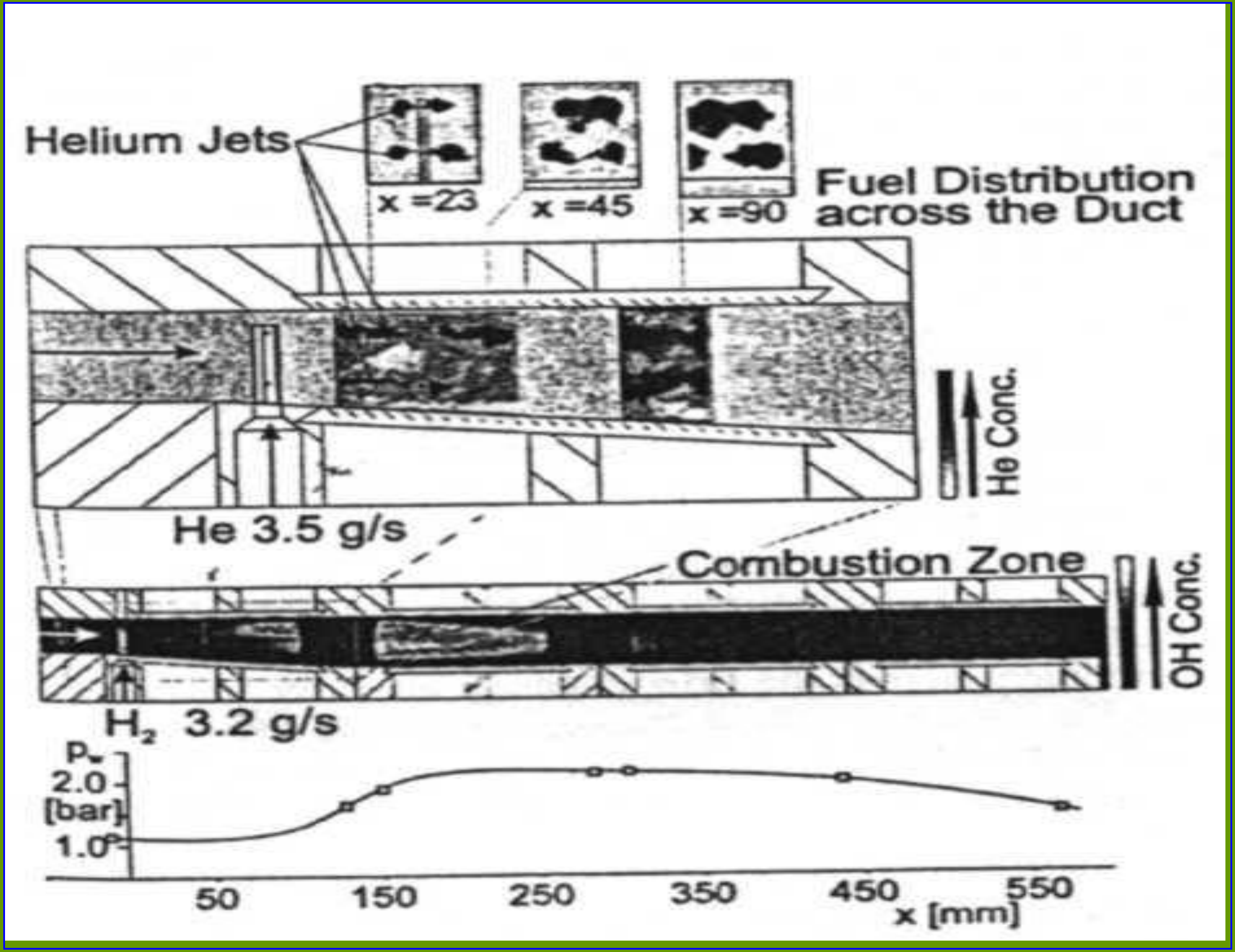


Mixing efficiency

Comparisons with mixing data.

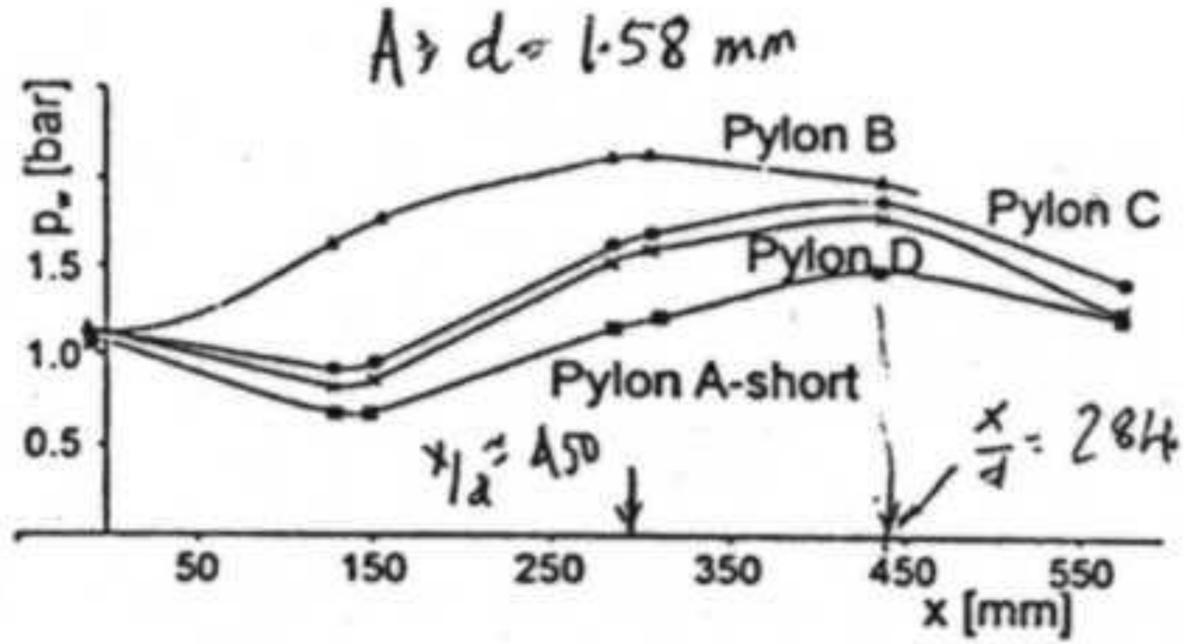
Mixing gets completed with x/d = 120 (perpendicular Injection).

Gruineg, Avarshikov and Mayinger, JPP, pp. 35 - 40 (2000)



Gas is injected from four locations from a pylon

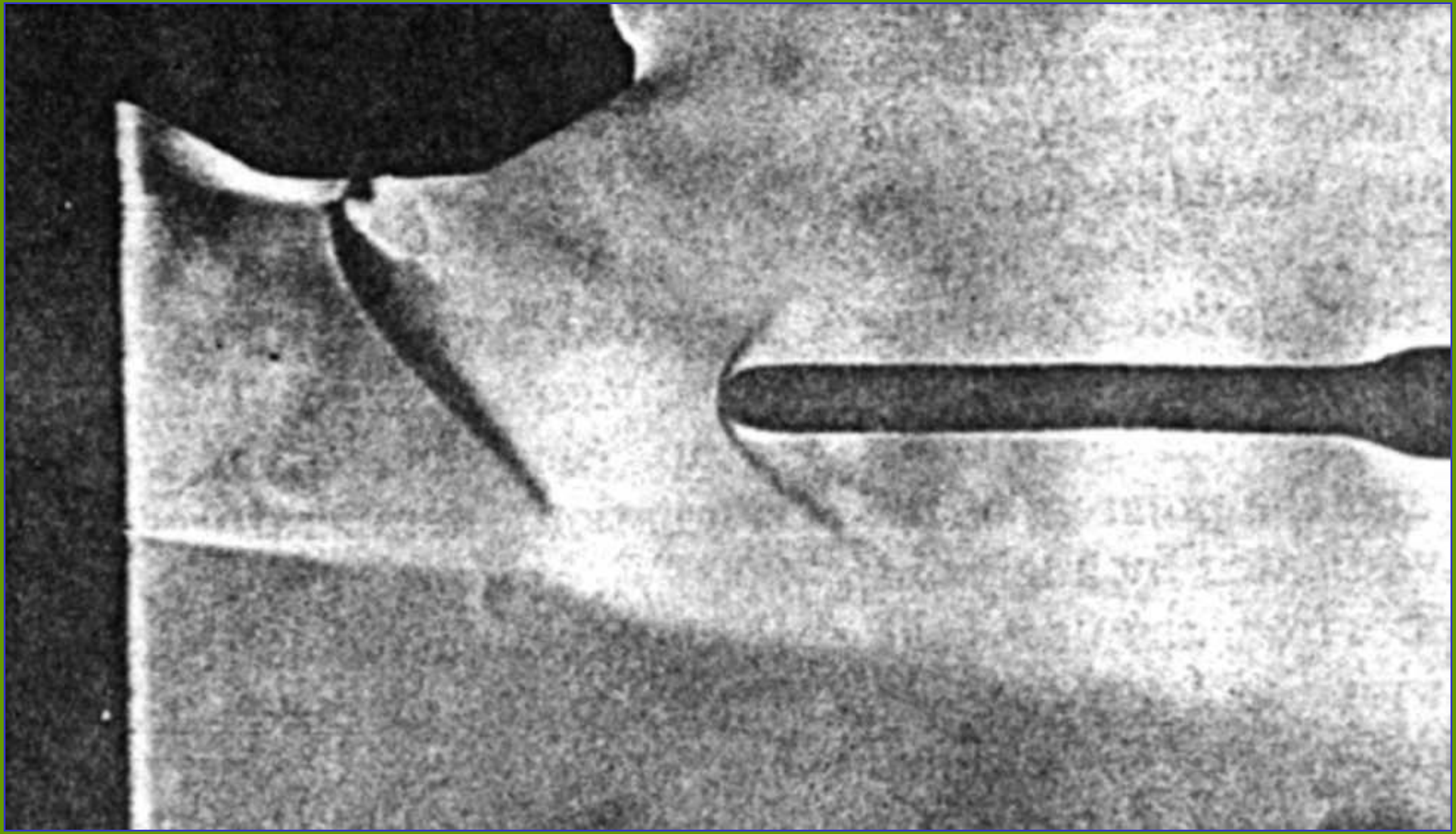
Gruineg, Avarshikov and Mayinger, JPP, pp. 35 - 40 (2000)



Static pressure distributions along the upper combustor wal for the tested pylons.

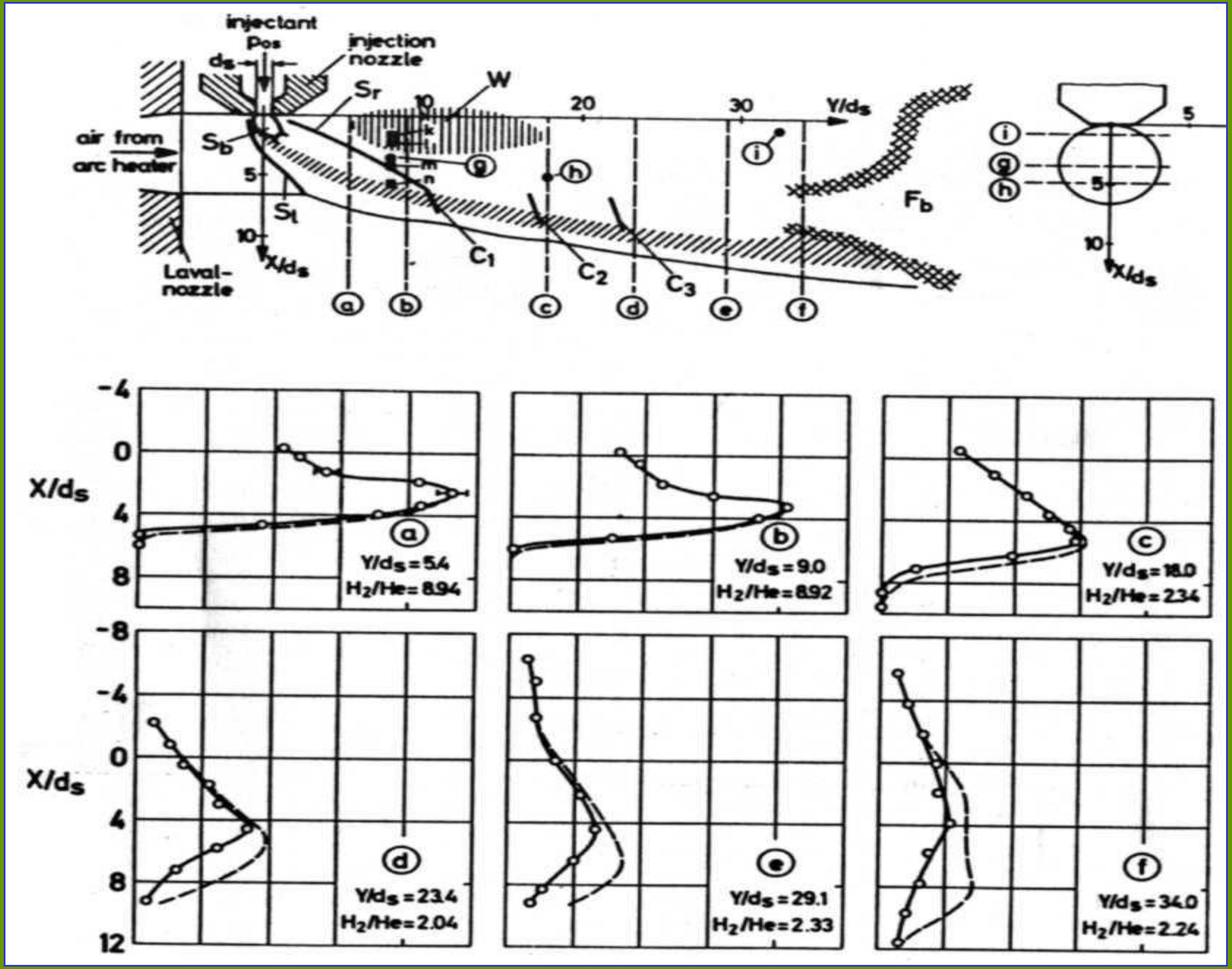
Combustion experiments in model combustors – X/d is between 300 and 450.

Wilhelmi, Baselt and Bier, 14th symp. (int) on combustion, 1973



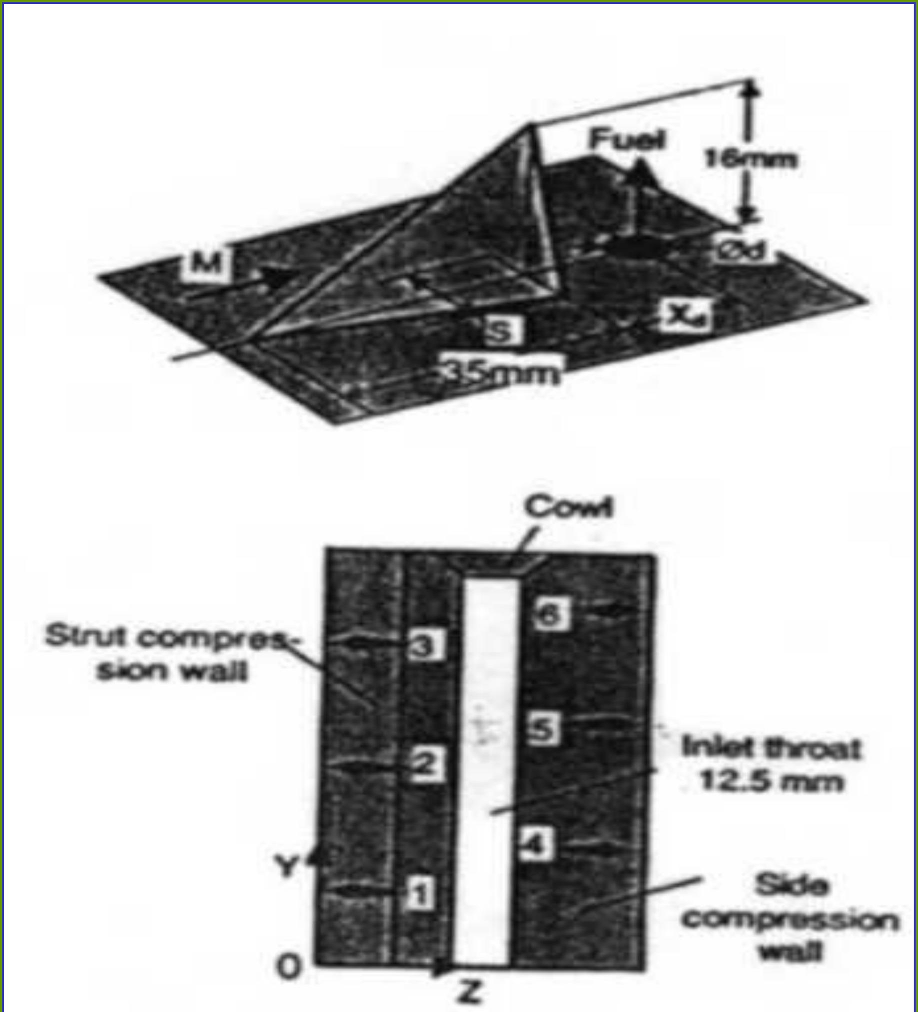
Mixing experiments with Hyd/Hel injected through a 1.56 mm nozzle vertically down into a M = 2, 1100 K stream

Wilhelmi, Baselt and Bier, 14th symp. (int) on combustion, 1973



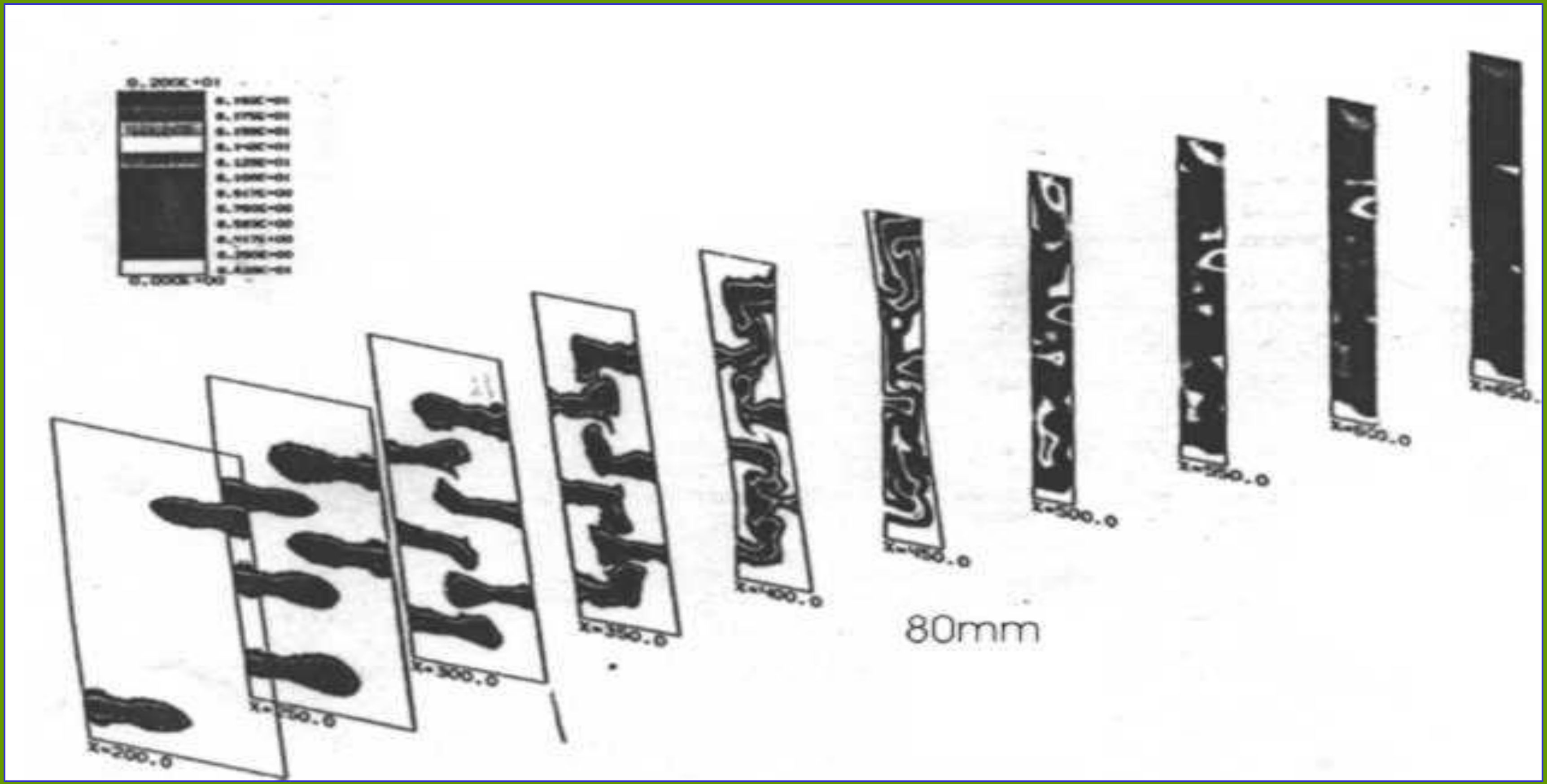
Mixing progress: At $Y/d_s > 34$ mixing is nearly complete.

Guoskov, Kopchenov, Vinogradov, and Waltrup, JPP, pp. 1162 – 1169, 2001



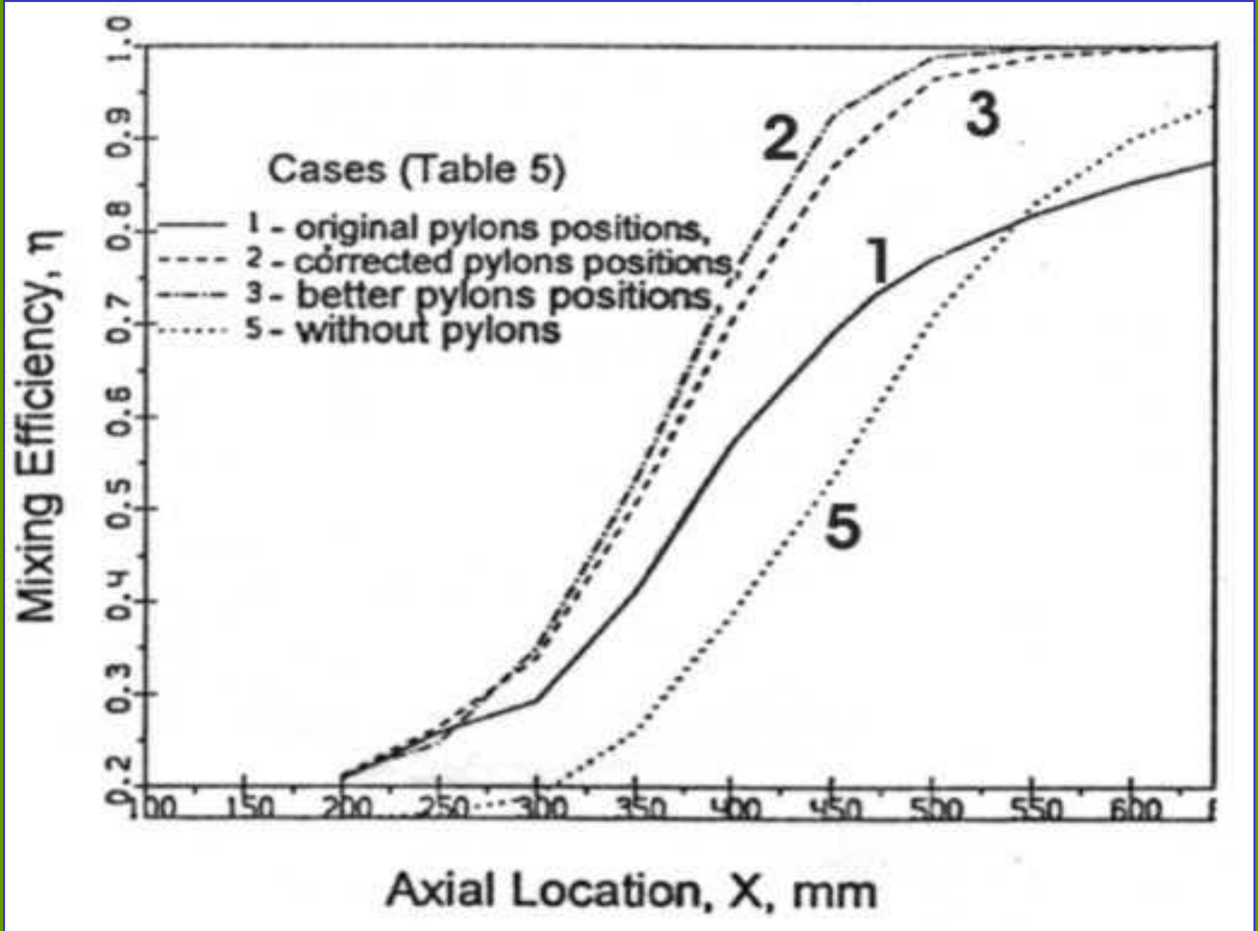
Experiments on mixing with C_2H_4 injection from perpendicular holes 3. 4 mm dia. downstream of 6 pylons located at different axial distances

Guoskov, Kopchenov, Vinogradov, and Waltrup, JPP, pp. 1162 – 1169, 2001



Pictures of mixed zones at distances 50 mm apart from 200 mm
Note that at 300 mm all jets are injected and at 650 mm all are mixed

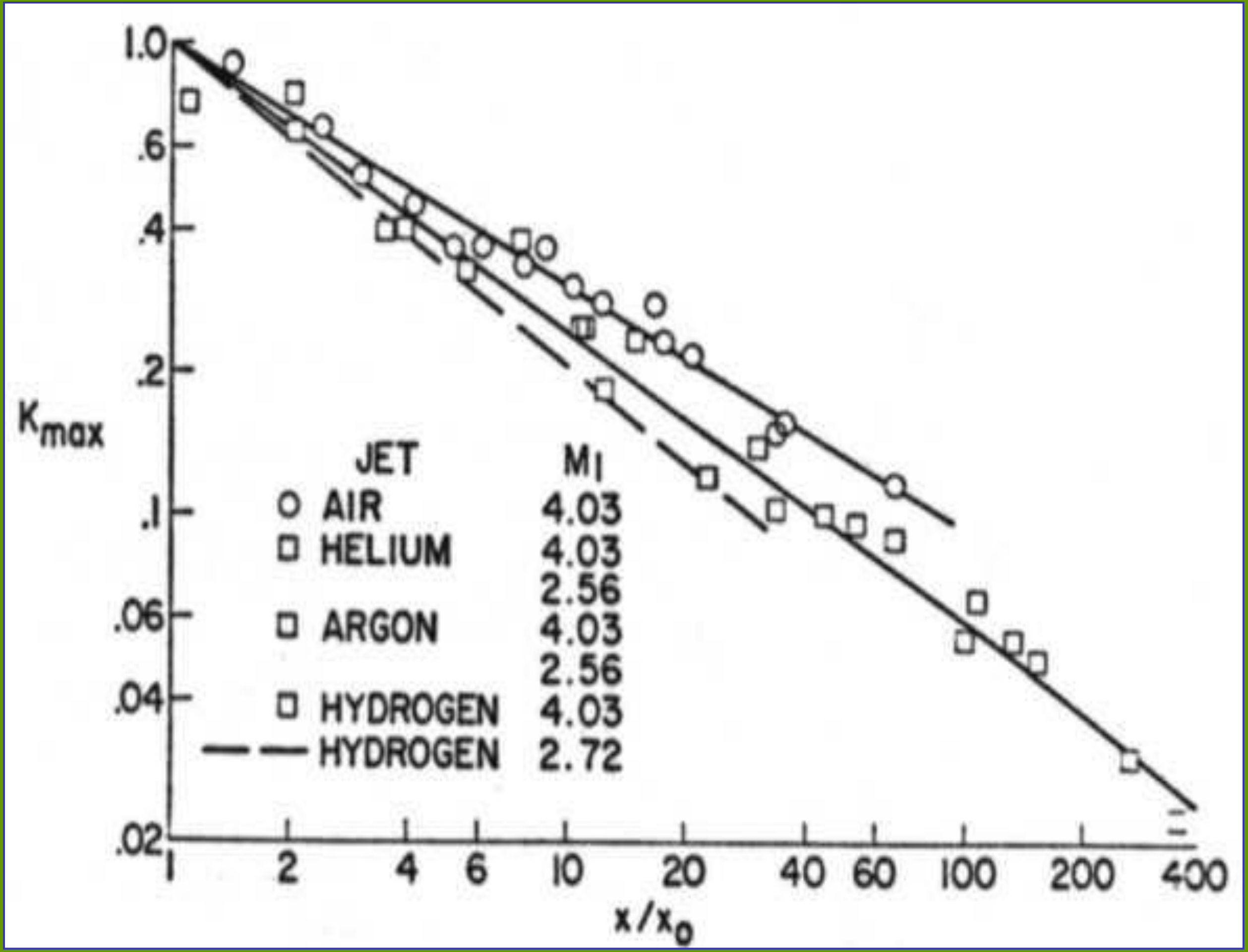
Guoskov, Kopchenov, Vinogradov, and Waltrup, JPP, pp. 1162 – 1169, 2001



Mixing efficiency for C_2H_4 injection at $M_\infty = 6$.

Note that in a distance of 350 mm all mixing is complete

Henry, 12th symp (Int) on combustion, 1969



The diagram shows the variation of maximum concentration with Distance normalized by $x_0 = 0.56\, d_0(\rho u)_f / (\rho u)_{air} \sim 0.1$ to $0.25\, d_0$ With these values, x/d_0 will be 40 to 100.

Summary of mixing data

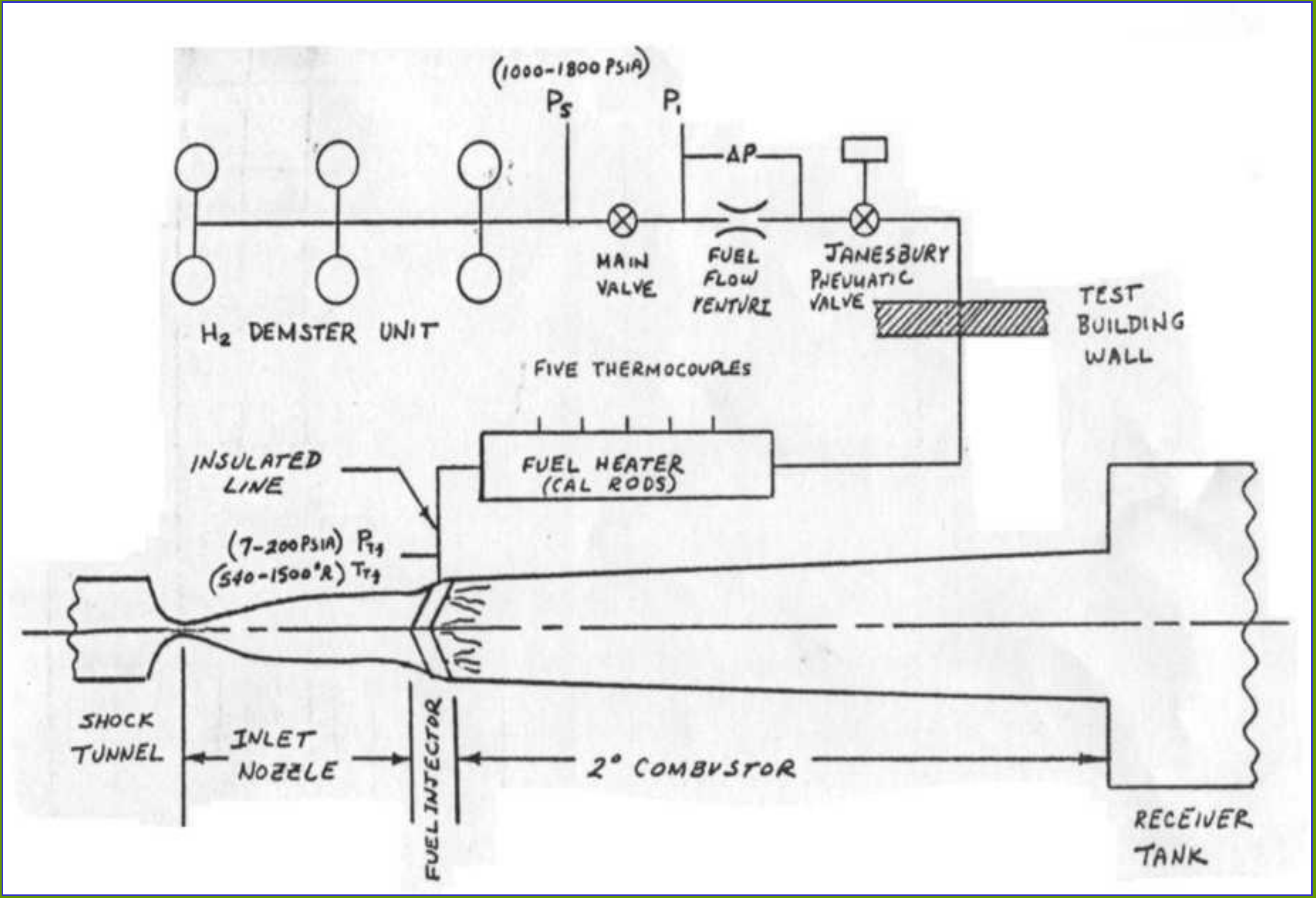
Author/s	(x/d) for 90 % mixing	
Gerlinger et al	700	(parallel Inj.)
Uneshi et al	120	(perpendicular Inj.)
Gruineg et al	284 to 450	(perpendicular Inj)
Wilhelmi et al	40	(perpendicular Inj.)
Guoskov et al	110	(perpendicular Inj.)
Henry	40 to100	

Mixing distances in perpendicular injection vary from x/d = 100,+50. By reducing the injector diameter, one can reduce the mixing Distance. If d is chosen as 0.5 mm, one would need a distance not exceeding 75 mm for mixing for perpendicular injection and about 300 mm for parallel injection.

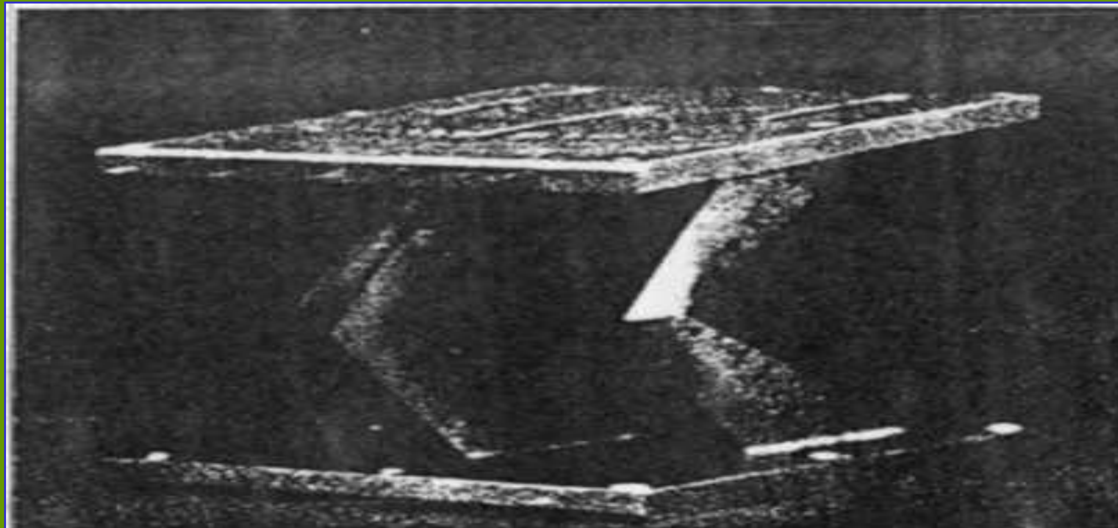
Combustion Experiments

- Marquardt's Work, 1964
- Waltrup, Dugger, Billig, and Orth, 1977
- Tomioka, Murakami, Kudo, and Mintani, (2001)
- Yu, Li, Chang, Chen, Sung, 2001

Marquardt's work – 1 (1964)

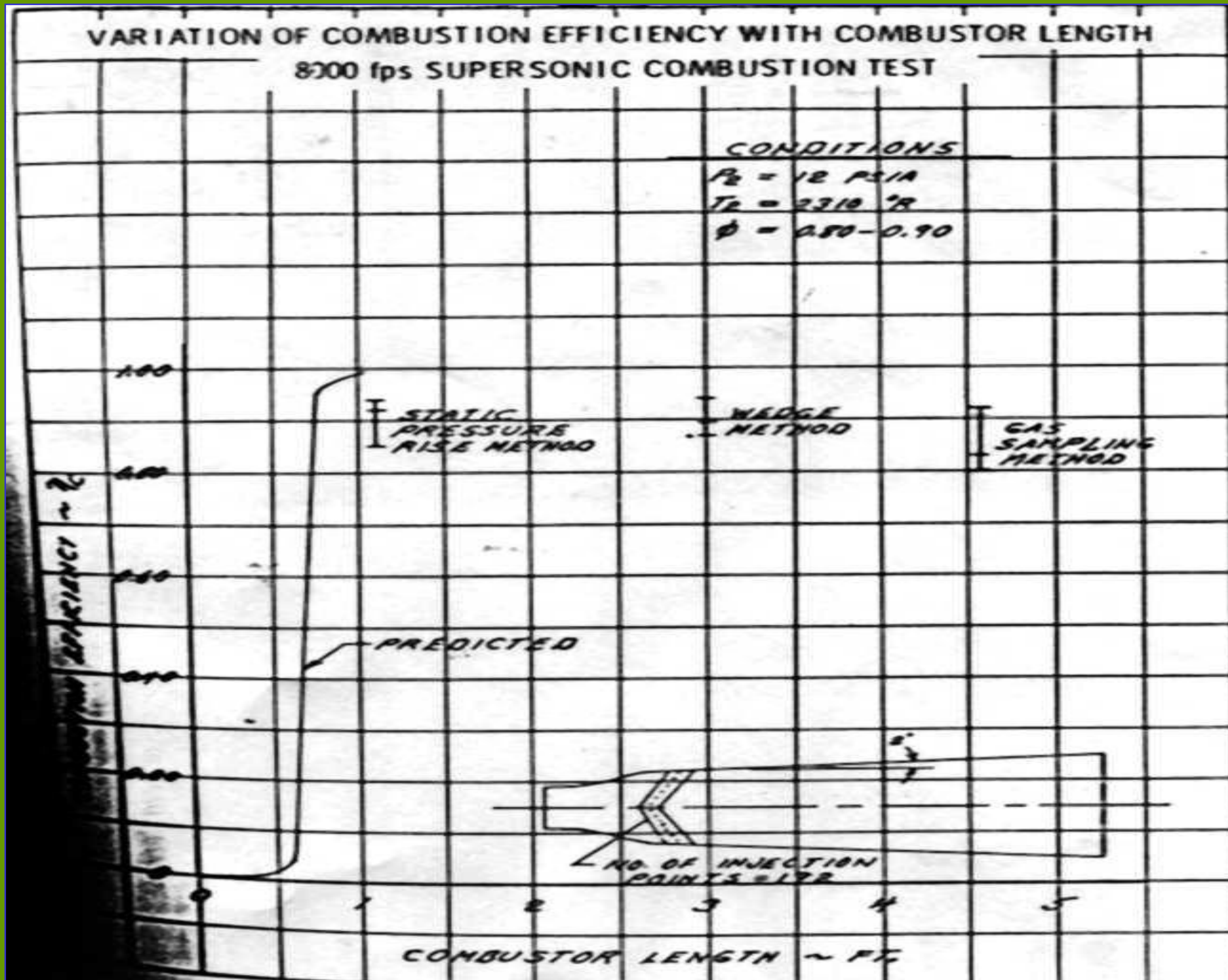


Marquardt's work – 2 (1964)

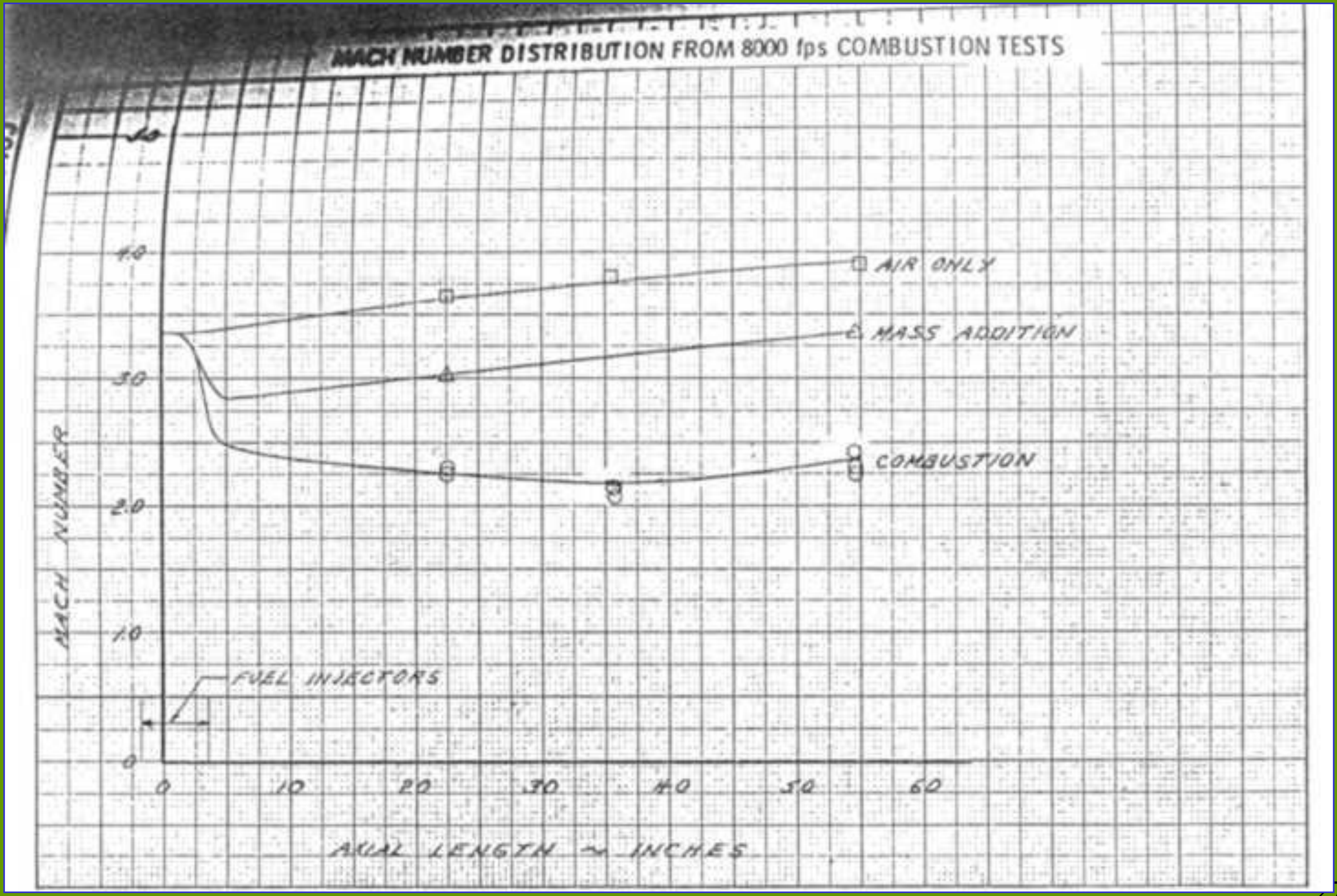


A. View Looking Aft

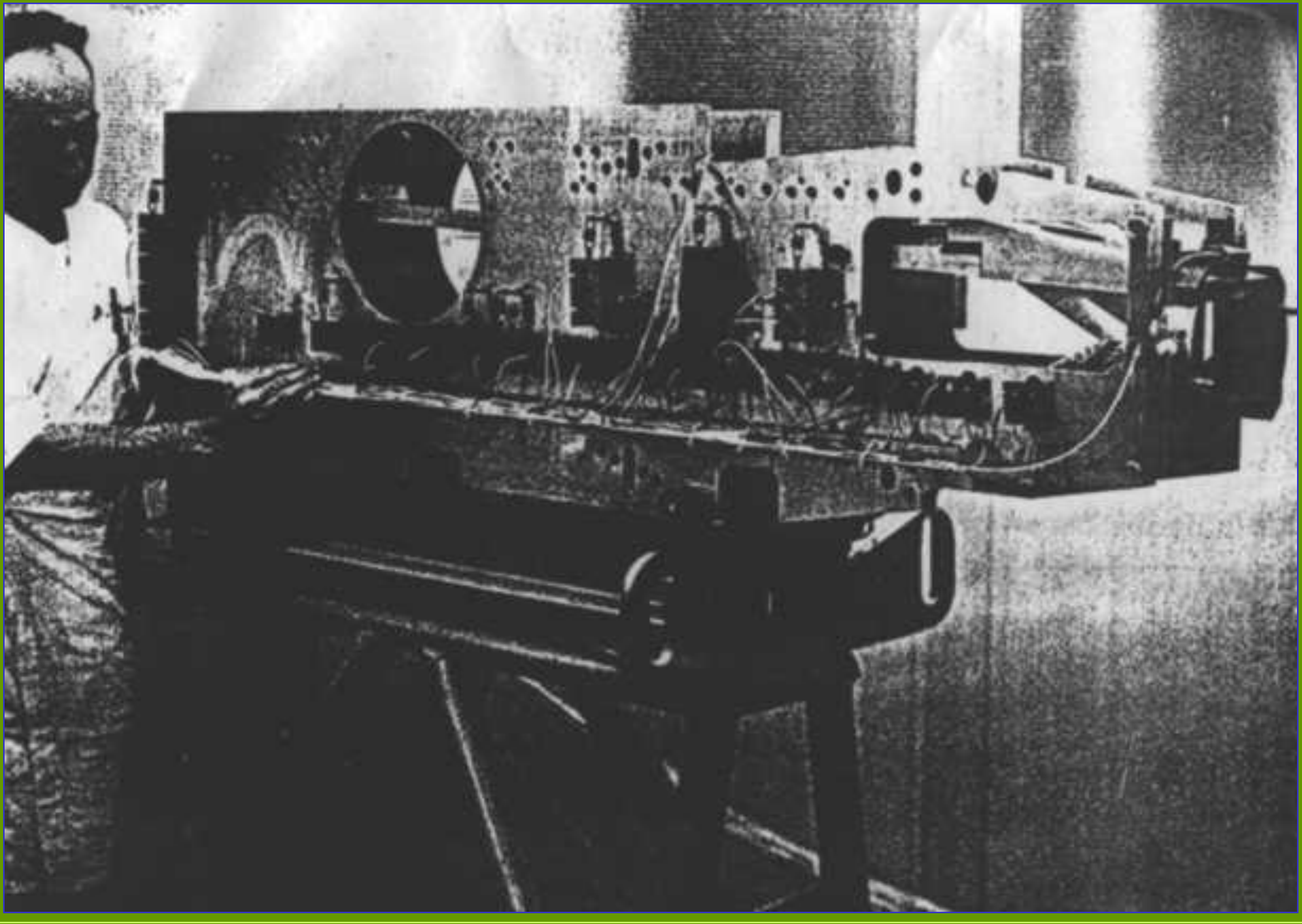
Marquardt's work – 3 (1964)



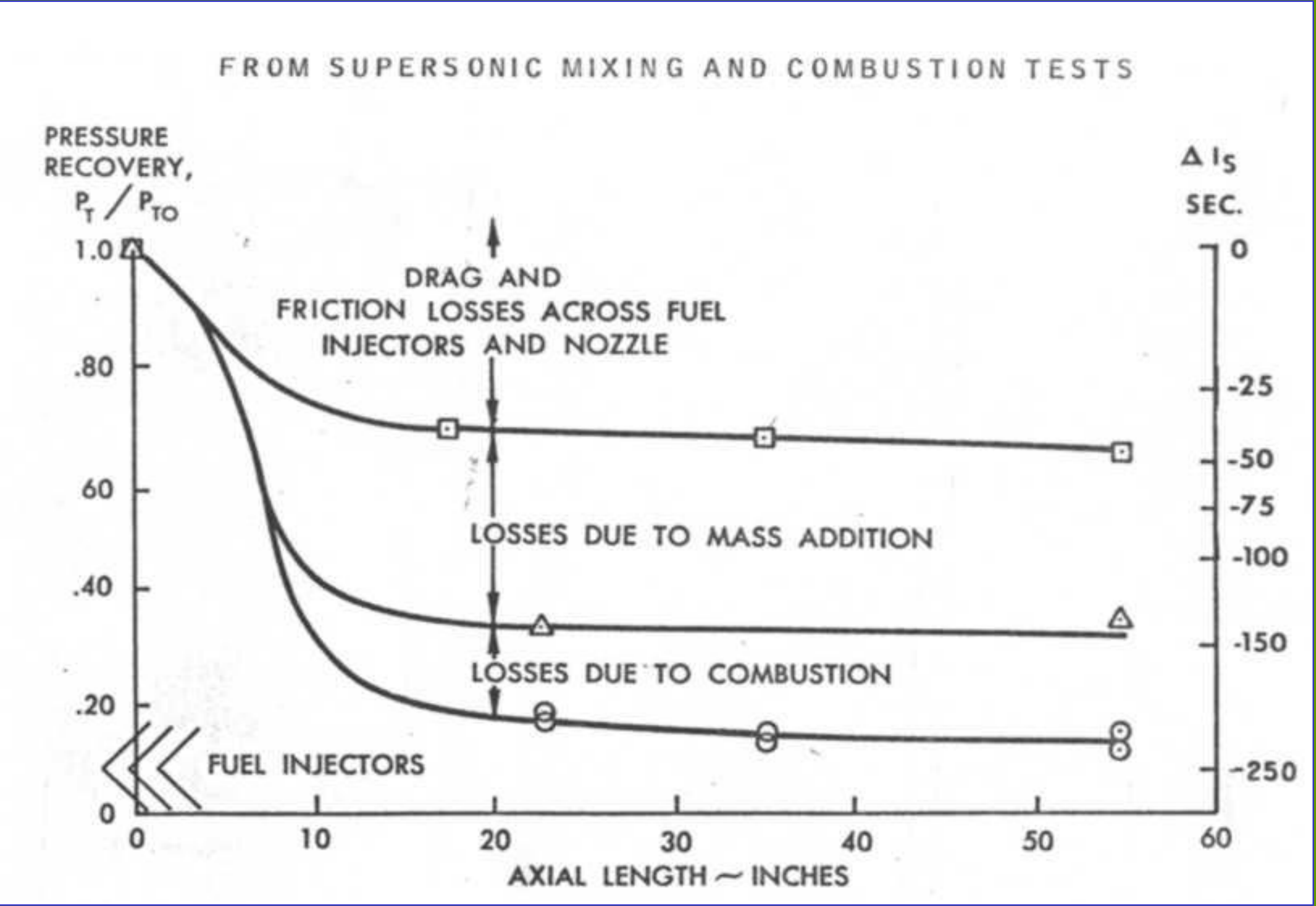
Marquardt's work – 4 (1964)



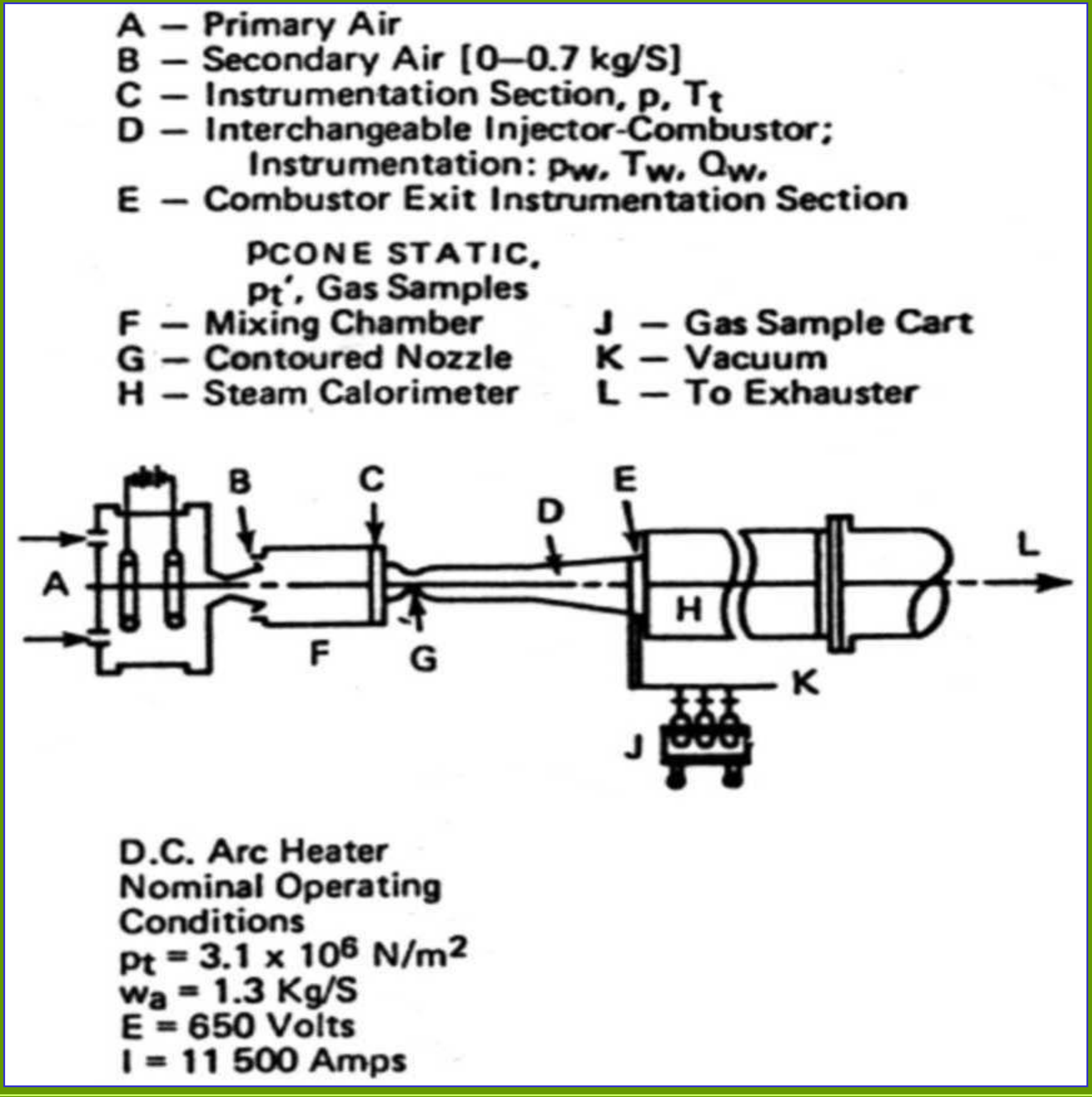
Marquardt's work – 5 (1964)



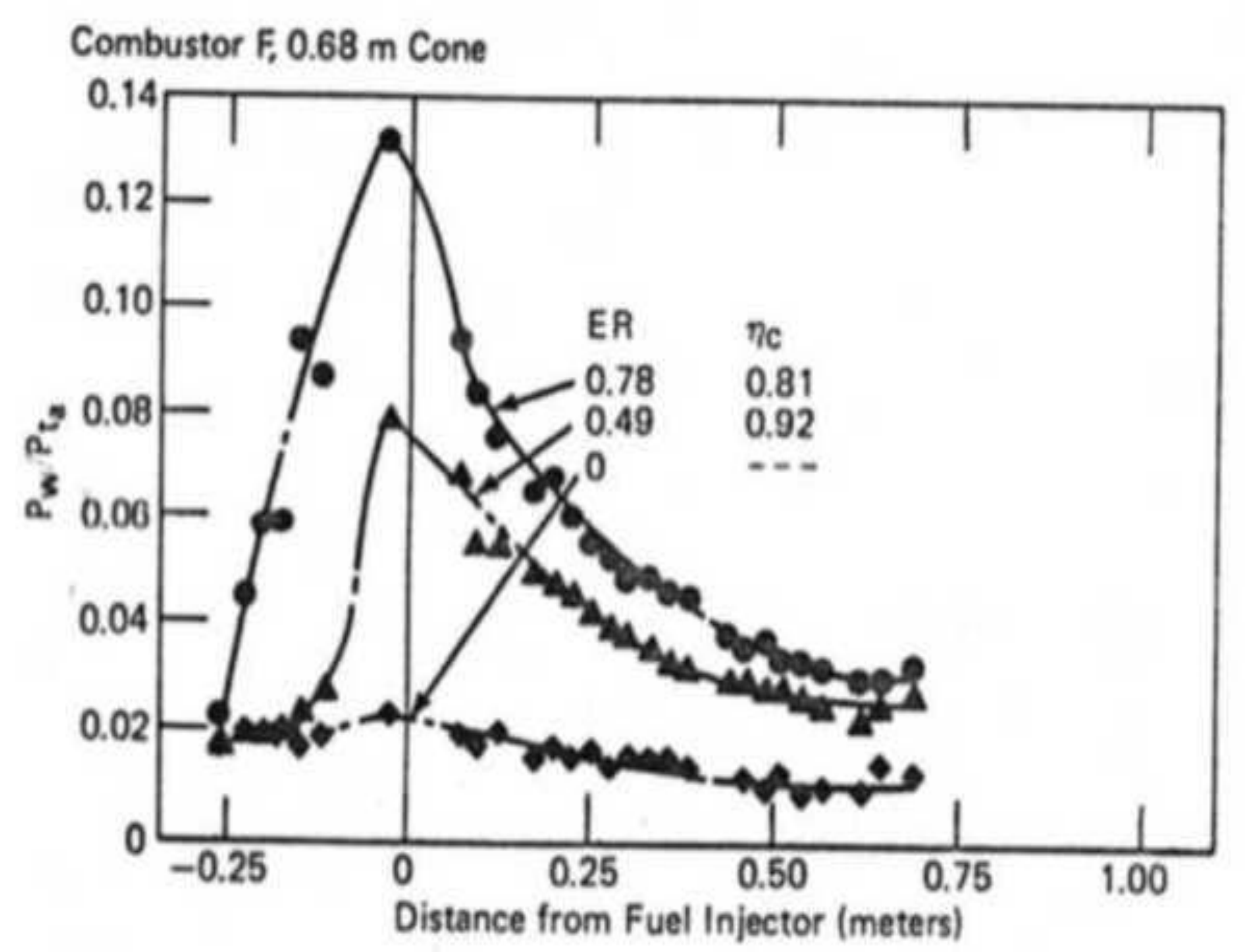
Marquardt's work – 6 (1964)



Waltrup, Dugger, Billig, and Orth, 16th Symp (Int) on combustion, 1977

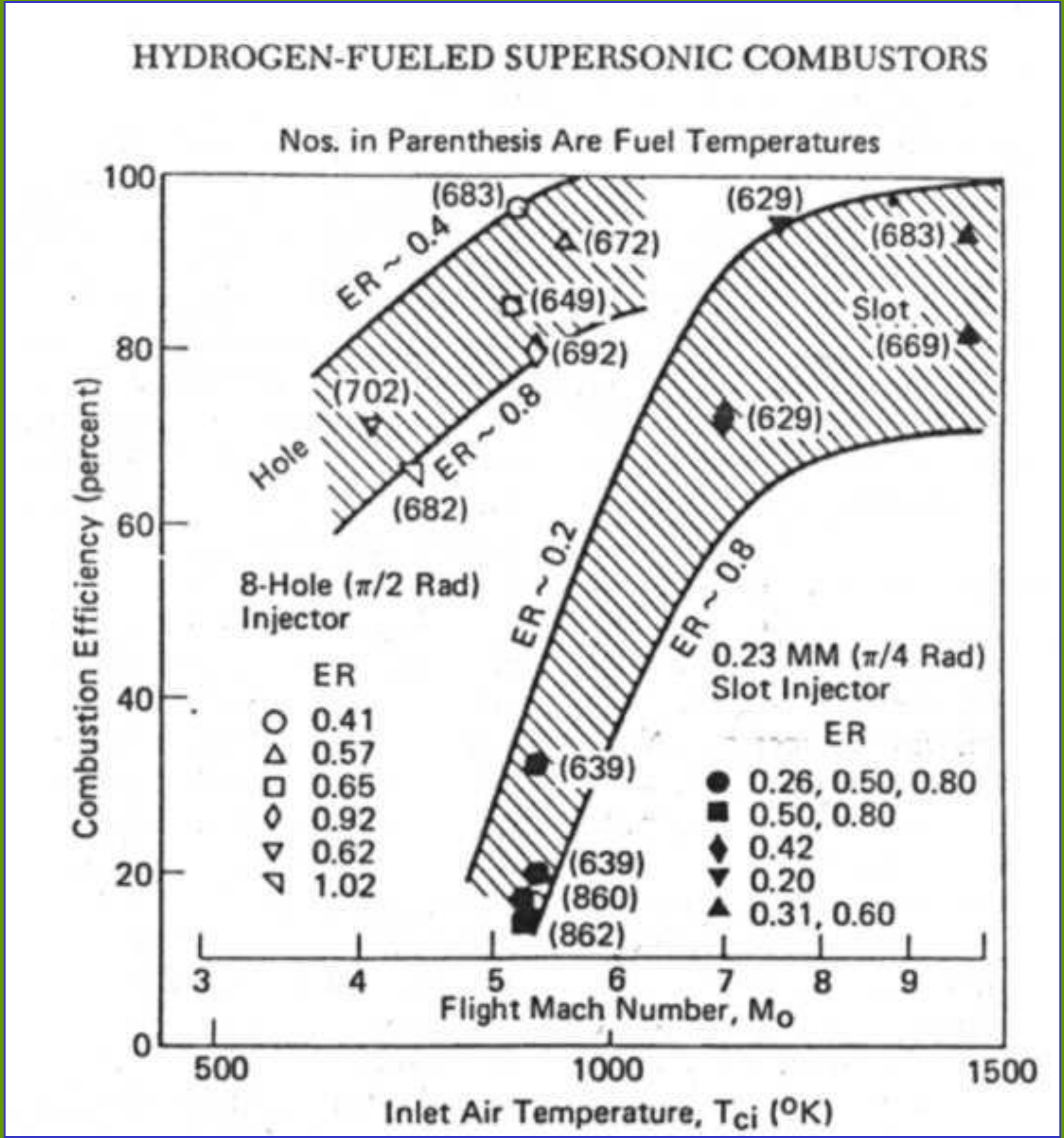


Waltrup, Dugger, Billig, and Orth, 16th Symp (Int) on combustion, 1977

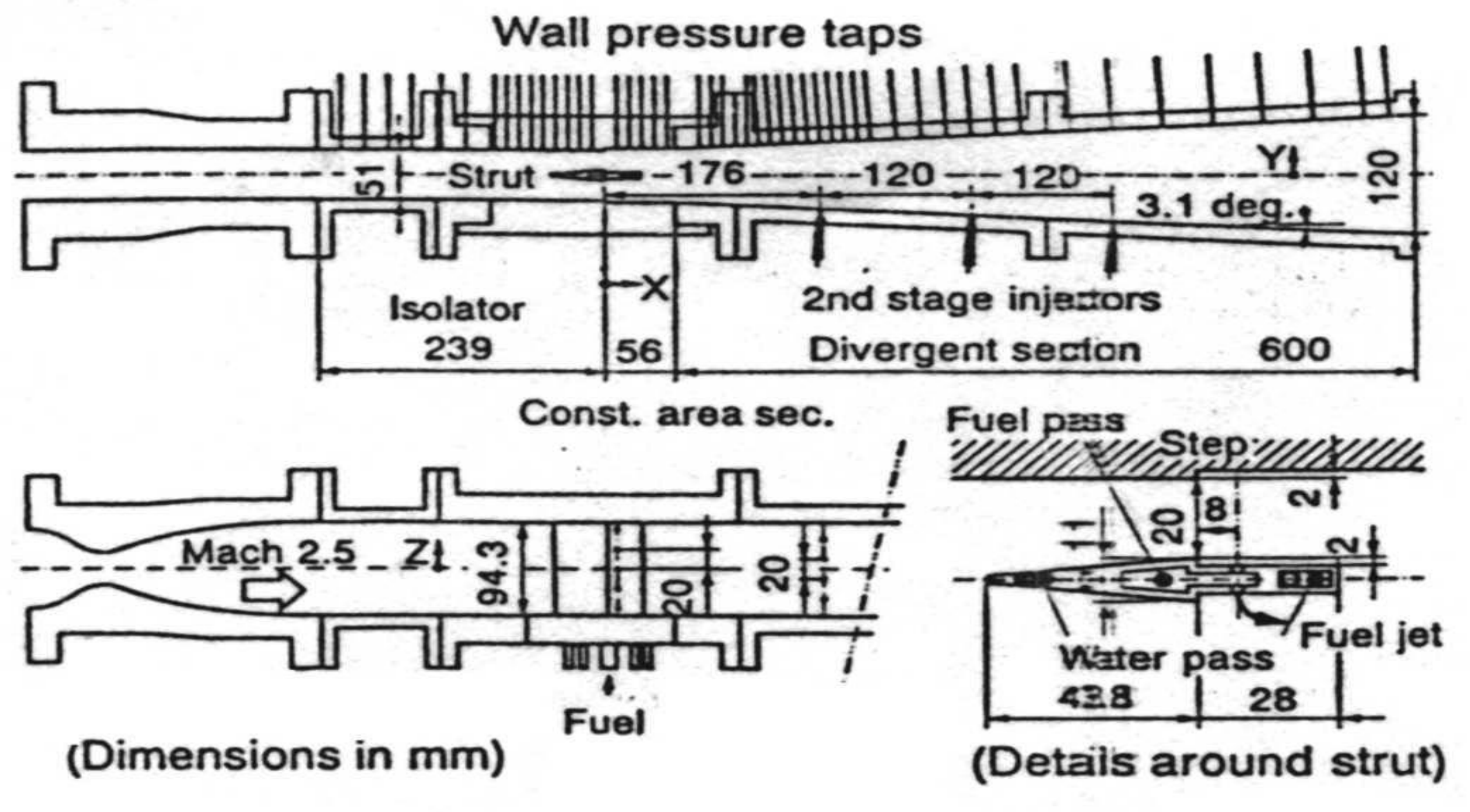


Side wall injectors for Hydrogen

Waltrup, Dugger, Billig, and Orth, 16th Symp (Int) on combustion, 1977



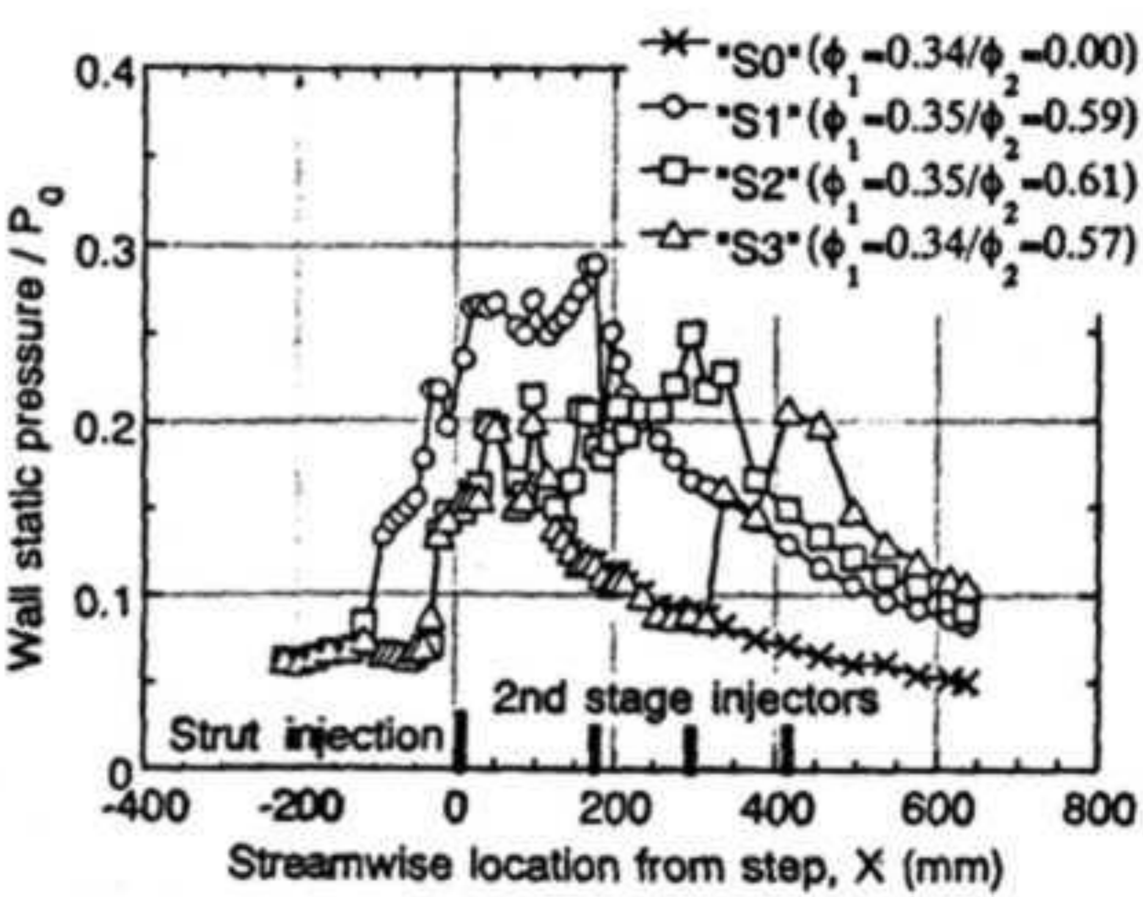
Tomioka, Murakami, Kudo, and Mitani, JPP, pp. 293 - 300 (2001)



Schematic diagram of combustor.

Hydrogen injection from the struts/sidewalls at three locations

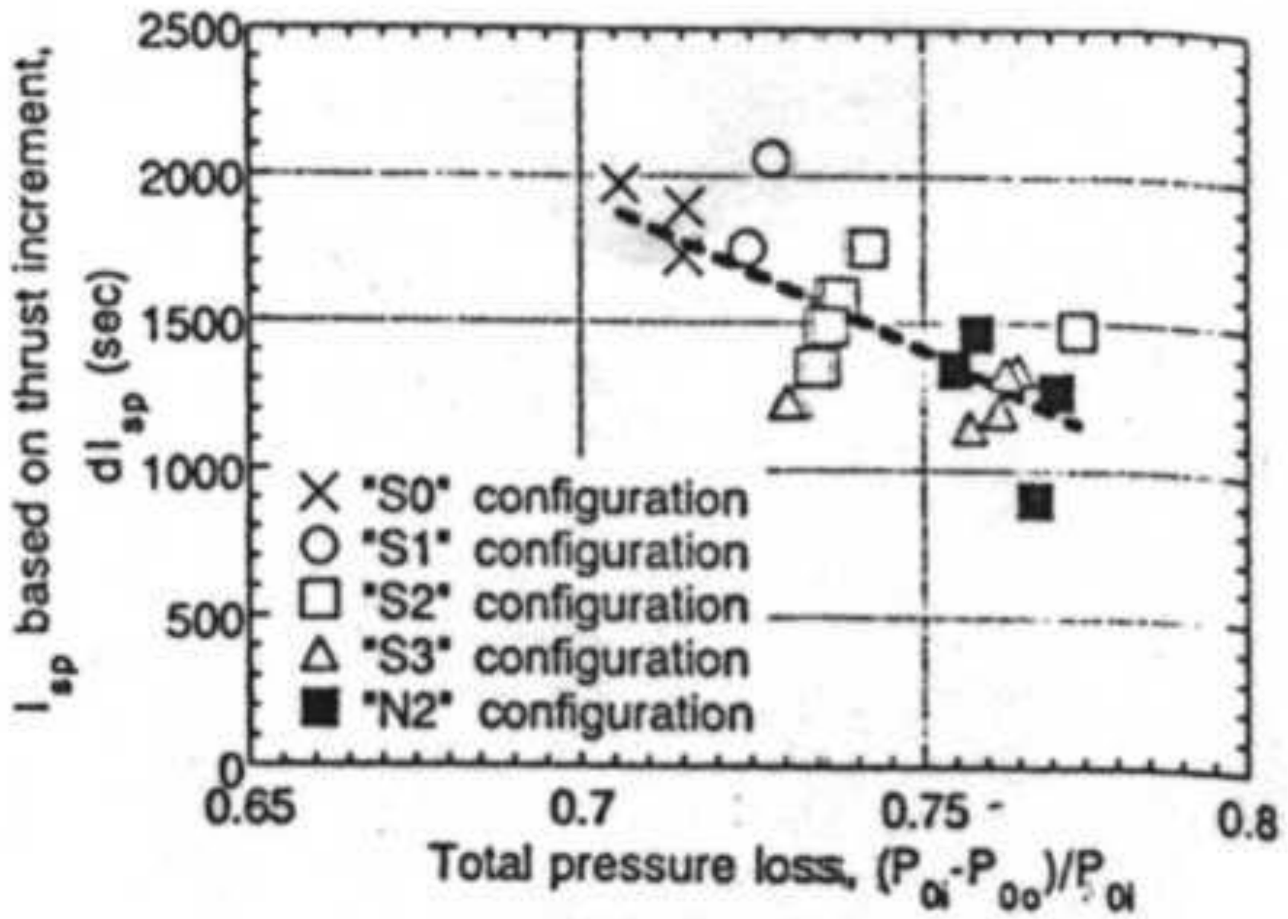
Tomioka, Murakami, Kudo, and Mitani, JPP, pp. 293 - 300 (2001)



Wall static pressure, distributions with S0, S1, S2, and S3 configurations.

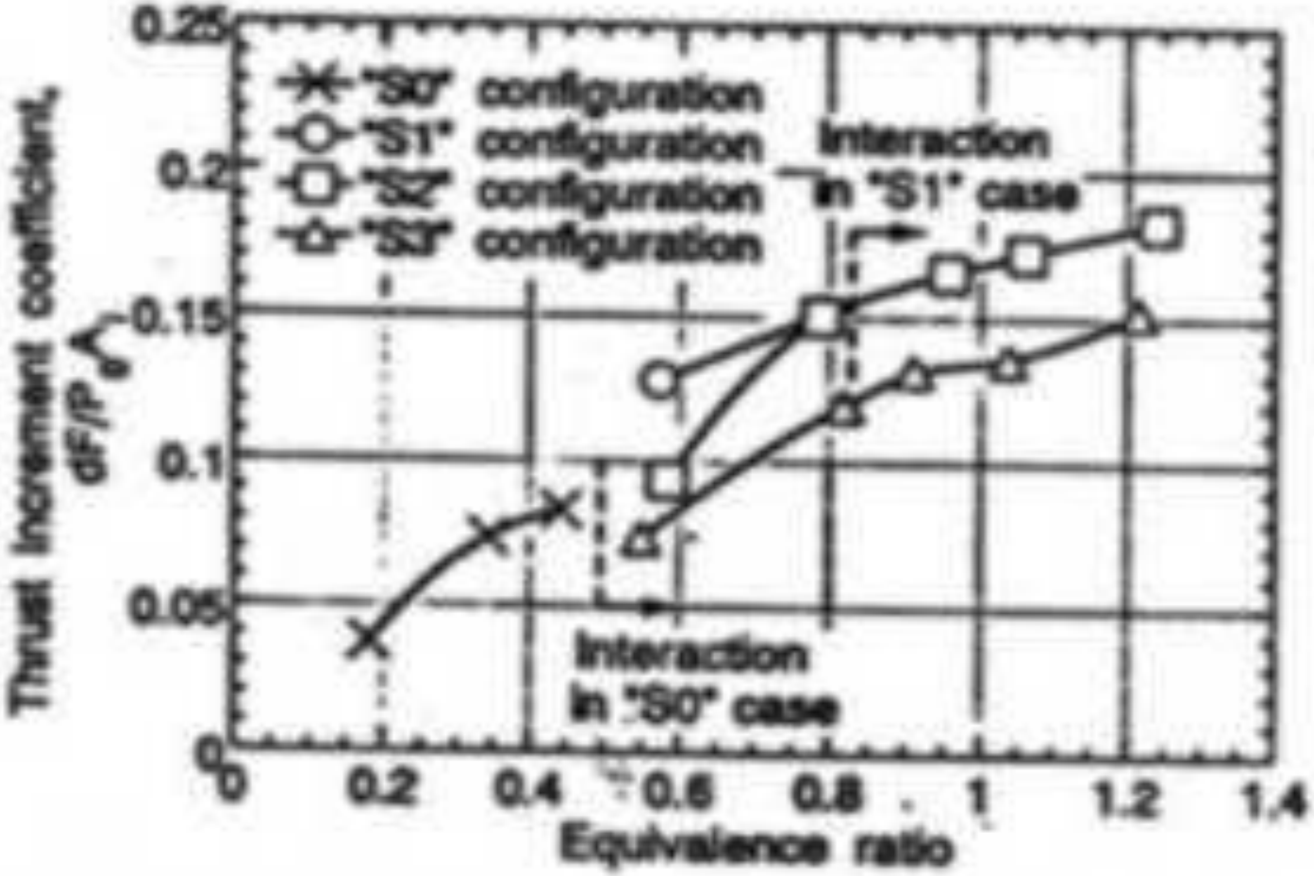
Note that even at Equivalence ratio = 0.91, combustion process is not coupled to the intake

Tomioka, Murakami, Kudo and Mitani, JPP, pp. 293 - 300 (2001)



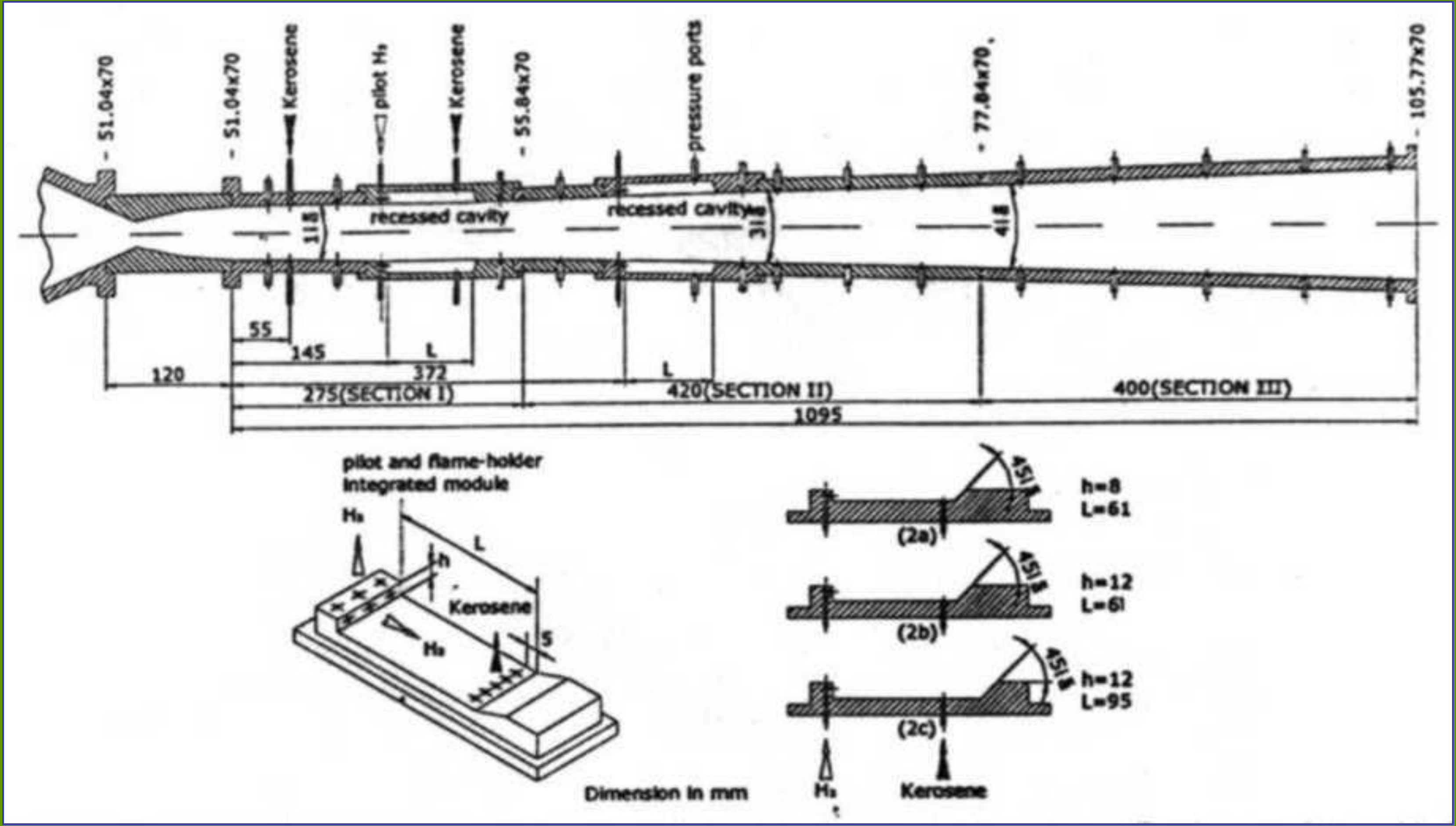
Relations between total pressure loss and specific impulse increment.

Tomioka, Murakami, Kudo and Mitani, JPP, pp. 293 - 300 (2001)



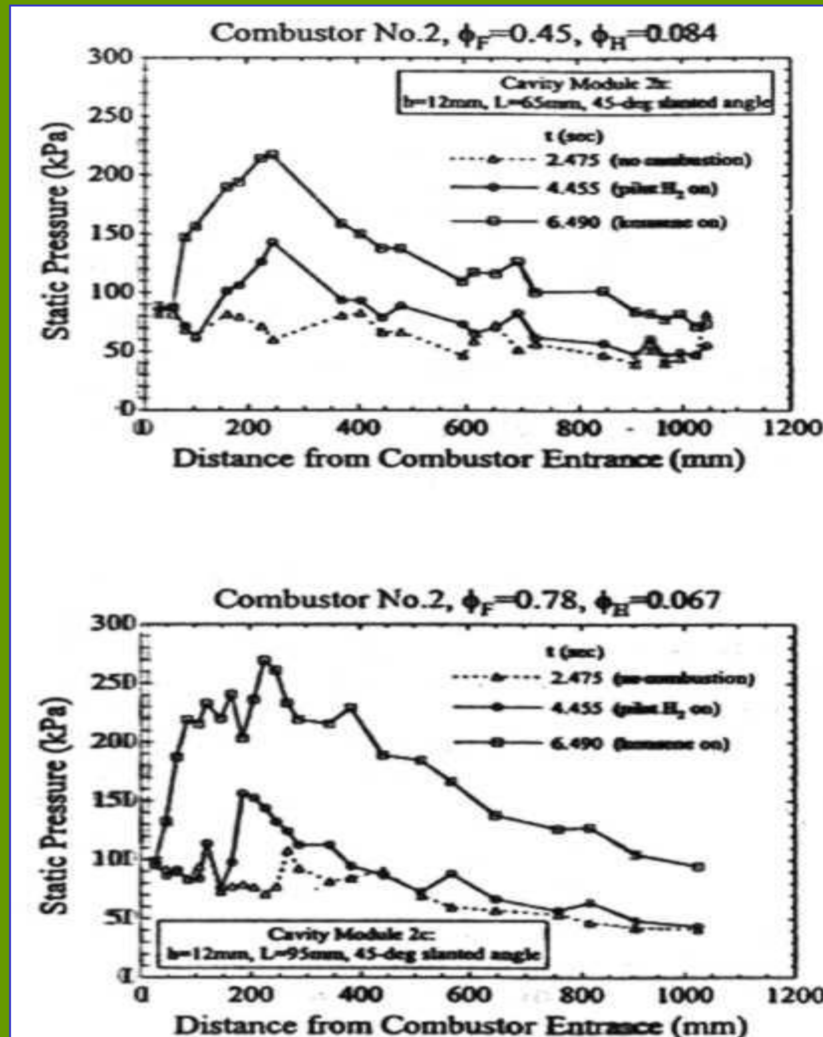
Thrust increment coefficients with S0, S1, S2, and S3 configurations.

Yu, Li, Chang, Chen and Sung, JPP, pp. 1263 – 1272, 2001



They have tested a number of cavities and fuel injection systems

Yu, Li, Chang, Chen and Sung, JPP, pp. 1263 – 1272, 2001



The tests used kerosene as the main fuel and a small fraction of Hydrogen as ignition/combustion facilitator.

Yu, Li, Chang, Chen and Sung, JPP, pp. 1263 – 1272, 2001

… This in turn suggests that the cavity configuration might not have significant effect on the combustion efficiency, although it does affect the minimally required pilot hydrogen equivalence ratio.

Summary of data

Author	Fuel Temp K	Air Temp K	Air M.	Stat. Pre. atm	Fuel Orifice Dia, mm	m(air), m(f)	A(Comb) /A(Fuel)	L m	φ Up to	$\{(dp/dx)/p_0\}_{max}$ (1/m)
Marquardt '64	~550 H_2.	1280	3.6	0.8	192 x ?	6, 0.15	127 x 84 /	0.8	0.9	12
Kanda et al, '97	150 H_2.	1550 (s)			24 x 1.5 + 94 x 0.5	0.14	200 x 250 /60 = 800		0.94	
Mitani, et al, '00	280 H_2.	1550 (s) 760(?)	2.0	0.2	24 x 1.5 (?)	4.76, 0.14	200 x 250 /42.4 = 1200	0.3	1.0	50
Gruenig et al, '00	150 H_2.	760 impure	2.15	1.0	1.58 or 4 x .66	0.33, 0.0032	25 x 27.5 /1.37 = 501	0.65	0.34	10
Owens et al, '01	H_2.	850 (s)	1.56		9 x 0.8 + 2 x 2.4		25 x 25 /13,5 = 46.2		0.71	4 - 35
Tomioka Et al, '01	300 H_2.	1550 (s)	2.5	0.5	10 x 2.5 3 x 8 x2.5		94 x 51 / 167.0 = 18.7	0.6	0.90	13
Yu et al,'01	300 Ker. + H_2	1811 (s) 900	2.5	1.0	3 x 1.2 (Hyd) 5 x 0.4 (Ker)	1.5,	51 x 70 / 0.48 (K)	1.0	0.78	7 - 8

Note that the length of combustor required is about 0.65 m for hydrogen and 1m for Kerosene. The typical residence time < 1ms

Hence,

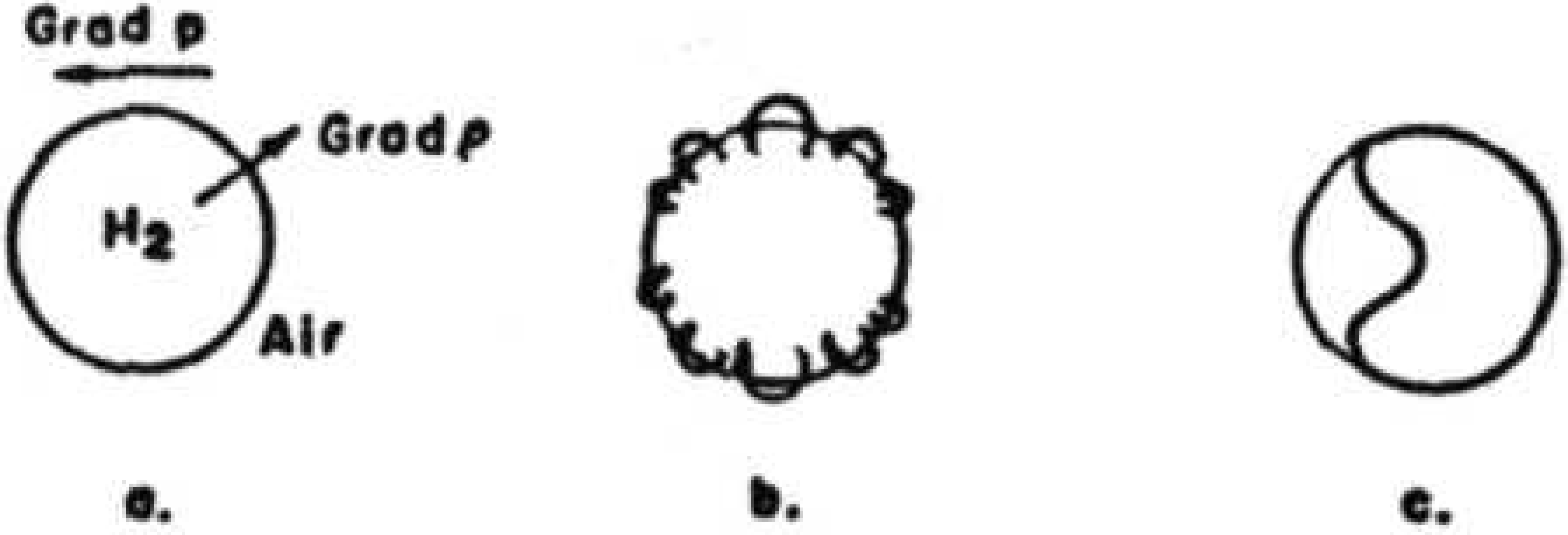
Designs that are simple and in conception no different from what one would do for an after burner for flame holding are able to hold the supersonic flame and complete the combustion in a length < 1 m. Some of them were evolved before the concern for slow mixing was even known. Is this concern a researcher's hype?

1. The convective Mach numbers in real cases are low.
2. Other effects aiding mixing must have been present….

One Fundamental input

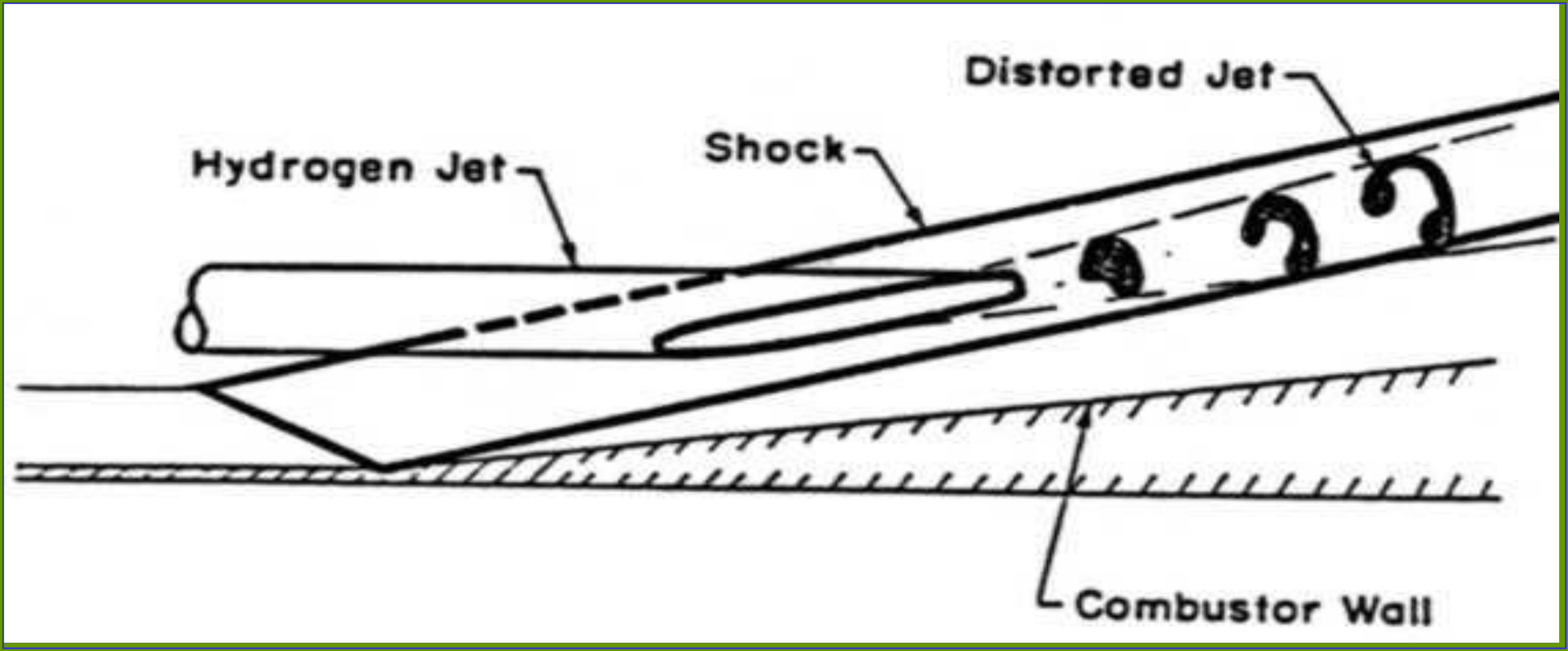
- Prof. Marble and colleagues have argued that the Rayleigh – Taylor instability induced at the interface of a light and heavy gas by a strong pressure gradient leads to the creation of streamwise vorticity

Marble , Hendricks and Zukoski, AIAA – 87 – 1880 (1987)



Vorticity and Distortion Induced by Shock Passage Over Hydrogen Cylinder in Air.

Marble et al, AIAA 90 – 1981 (1990)

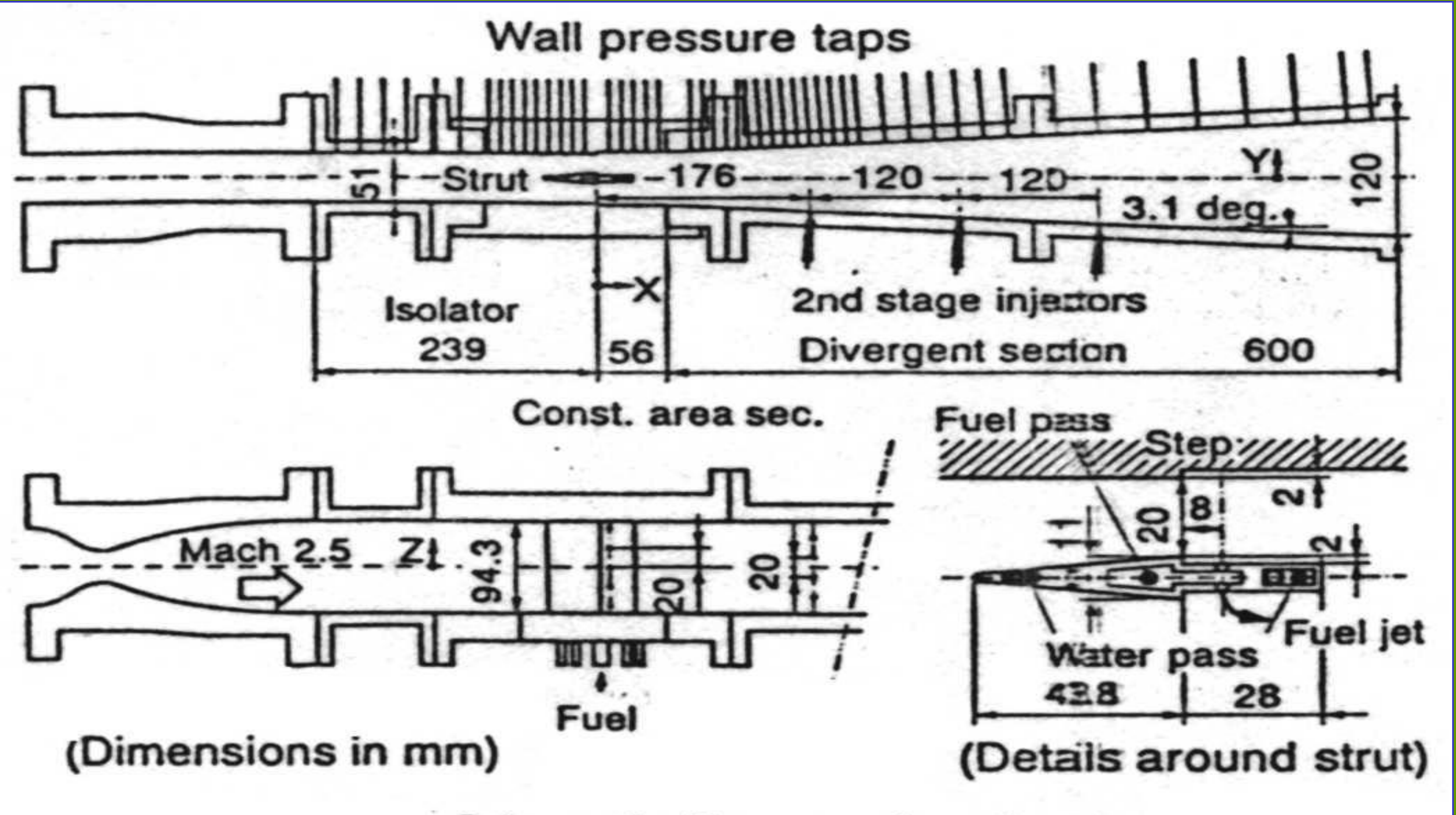


Every supersonic reactive flow field in an engineered hardware has many protuberances leading to weak/strong shocks bouncing through the system. Hence the above effect is naturally incorporated into the flow field.

An Isolator for a scramjet

- A constant area section of sufficient length is introduced between the air intake and the combustor, so that
- Under varying flight conditions the upstream interaction of the combustor does not reach the air intake.
- Many experiments – Gruber, Mathur and Billig, and others from the USA, Mitani, Kanda, Tomioka, Chinzei from Japan and others as well have used in tests.
- This has happened to an extent that the absence of isolator is considered unthinkable in design.

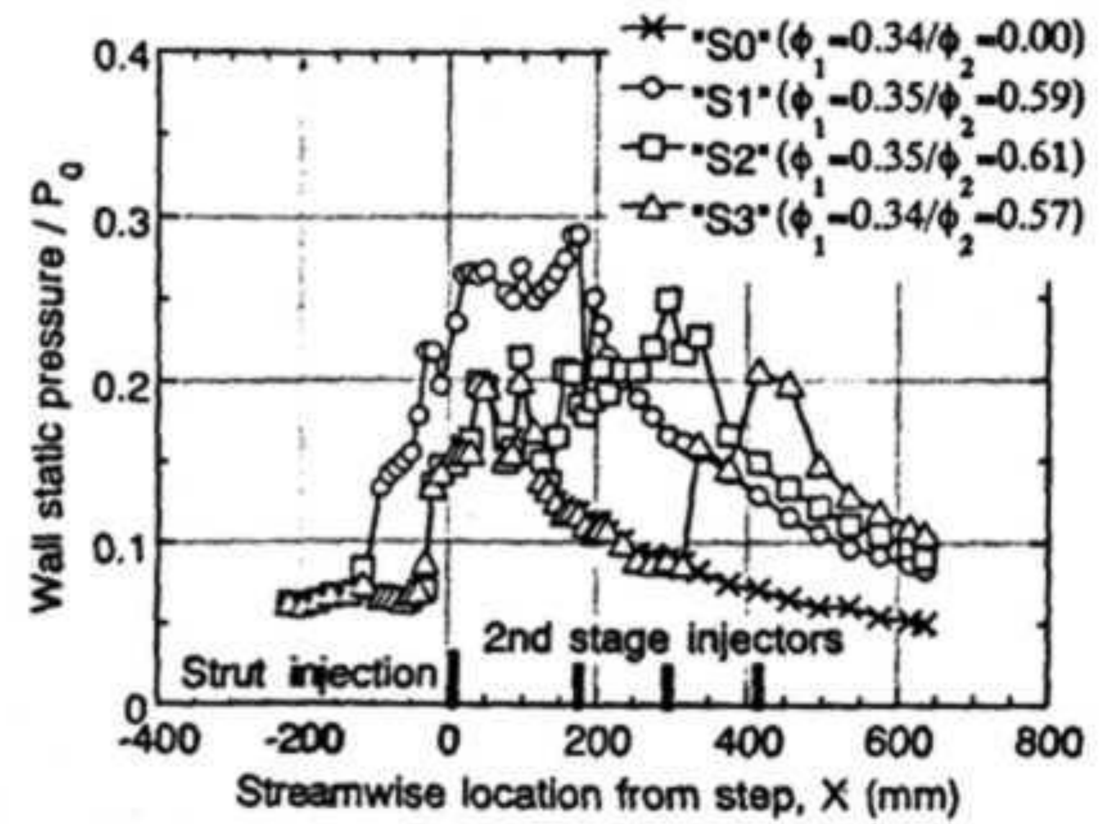
Tomioka, Murakami, Kudo, and Mitani, JPP, pp. 293 - 300 (2001)



Schematic diagram of combustor.

Notice the isolator 239 mm long

Tomioka, Murakami, Kudo, and Mitani, JPP, pp. 293 - 300 (2001)



Wall static pressure, distributions with S0, S1, S2, and S3 configurations.

Note that for cases S2 and S3, the sharp rise in pressure occurs with very little of the isolator.

Isolator - contd.

- There are other experiments in which the irrelevance of isolator is clear.
- There are cases where the isolator is shown to be necessary could be handled differently without it.
- For fixed flight conditions, or even a fixed set of flight conditions, one can design the fuel injection system so ***that graded heat release occurs in the combustor*** so that upstream interaction can be eliminated.
- This would help the elimination of a lossy intermediate element.

Incomplete Combustion as a design goal? - 1

- Prof. Swithenbank enunciated thus:

Mixing efficiency, a combination of stagnation pressure loss due to turbulence, quantified simply – $\eta_m = 1 - 3\,(u'/U)^2_{max}$

- Combustion efficiency improves due to turbulence –

$\eta_c = 1 / [1 + 1/\{50\,(u'/U)_{max}\}]$

The combination has an influence on the Specific impulse such that there is a maximum with turbulence level and therefore with combustion efficiency. He therefore predicated that one should not burn the fuel to an efficiency higher that what is permitted as above.

Incomplete Combustion as a design goal? - 2

- The analysis is simple no doubt, but tends to be "simplistic", since the flow is complex and 3-D; it is difficult to imagine if the chracterization of the entire process goes this way.
- No other studies seem to have followed the principles stated above. High combustion efficiencies seem to have been achieved.
- Instead of achieving less than 100 % efficiency: Cannot one burn less fuel ($\varphi < 1$) but completely so that heat release is limited and hence losses too?.

Final Remarks

The design of scramjets can follow the traditional principles excepting that the high speeds can be very punishing in terms of performance loss for small mistakes. This only requires advanced tools of design like *calibrated* CFD to enhance the reliability in the design.

Thank you